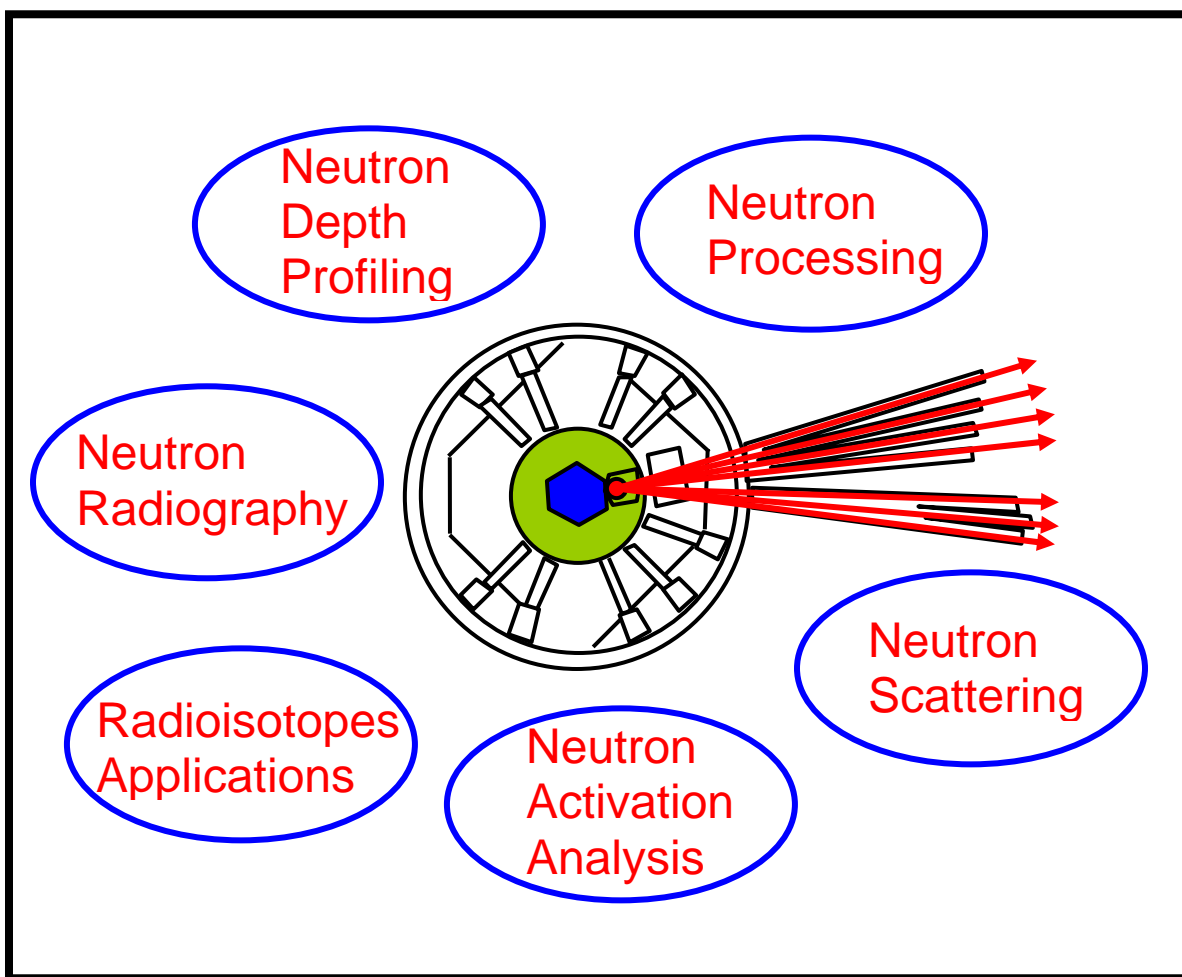


# PRACTICAL NEUTRON APPLICATIONS

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## **PREFACE**

There are many practical applications that use neutron sources such as nuclear research reactors. This author has developed interest in such applications as a “pet project” over the years and has collected material related to this topic most of it at the University of Missouri Research Reactor for five years in the late 1980s then at the National Institute of Standards and Technology Center for Neutron Research for the past 20 years. The first written document in this topic was put together in 1992 as an internal report (NIST Special Publication 844) entitled “Practical Applications of Nuclear Research Reactors”. The advent of the internet (with its knowledge databases and search engine capabilities) has prompted this author to revise and complete this project for a series of lectures for non-experts in the nuclear field.

Subject matters are covered at an undergraduate level and require familiarity with introductory physics background only (elementary particles, elements of the periodic table, etc.). Nuclear reaction basics are described and used to build up a wide range of practical neutron applications. The material used is not from cutting edge research, but rather pitched for an educational goal. Subject matters are therefore not meant to be thorough and complete but rather descriptive and illustrative.

The following scientists have been helpful with discussions as well as have freely provided material: John Farmer, Gary Ehrhardt, Mike Glasscock and Robert Brugger from the University of Missouri-Columbia, Greg Downing, David Jacobson, Russell Watson, Thomas Gnäupel-Herold, Rick Paul and Charlie Glinka from the National Institute of Standards and Technology, and Kenan Ünlü from the Penn State University.

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## INTRODUCTION

When someone thinks of nuclear energy, the first things that come to mind are nuclear weapons and electrical power production. While it is true that these are the most important applications, there is a host of other applications related to nuclear science. The focus here will be on such applications. They all use neutrons that are produced using (mostly) nuclear research reactors.

This project describes a wide range of practical neutron applications. After a brief history of how this field grew, some elements of atomic physics and nuclear physics, and familiarization with neutron production, the neutron activation analysis and radioisotopes applications are covered.

Neutron activation is an analytical technique used to detect and quantify minor and trace levels of elements for a wide variety of applications encompassing many fields of physical, natural and life sciences. It consists of irradiating a sample and measuring the gamma activity emitted from it. NAA is used for various biomedical, geological, archeological, forensic science, art history, industrial, and environmental applications. This technique has existed as long as reactors have existed.

The need to use radioisotopes has been growing ever since they were discovered. Natural radioisotopes (Po, Ra) have been known since before the discovery of the neutron (in 1932) while artificial radioisotopes were discovered after the advent of nuclear reactors and particle accelerators. Artificial radioisotopes are produced from stable isotopes upon irradiation. The radioisotopes then decay and emit charged particles and gamma rays. The two most common ways to produce radioisotopes are particle accelerators and nuclear reactors. Particle accelerators produce mainly positron ( $\beta^+$ ) emitters while nuclear reactors produce mainly beta ( $\beta$  or electron) emitters. Particle accelerators inherently produce small amounts of radioisotopes compared to nuclear reactors. Practical applications in medical, industrial, agricultural, and environmental fields are described. Radioisotope cobalt-60 is at the core of so many applications that it has received a chapter of its own.

Three kinds of applications are sometimes referred to as "neutron interrogation". These are neutron radiography, neutron gauging and neutron depth profiling. Neutron radiography is another very much unknown application (compared to x-ray radiography). Yet, this technique is very useful for visualizing contrasts between various elements as well as in following real time dynamics of hydrogen-containing fluids. Neutron gauging is used in mining operations to produce indirect imaging of geological layers, in industrial bulk process streams for the grading of ores, and in commercial applications to determine the hydrogen and nitrogen contents of various foodstuffs (nuts, grains, etc.). Neutron depth profiling is an effective technique for the characterization of the density profile of some prompt charged particle emitters following neutron absorption (boron for example) close to a sample surface.

The forms of radiation produced in reactors (fast neutrons, gamma rays) have strong "effects" on materials. The word "damage" is sometime used in this context with a negative connotation, whereas these effects can be useful such as in track etching (a form of age determination over a range of 10 billion years), in the transmutation doping of silicon to produce semiconductors, in the coloration of gemstones through the introduction of color centers, and through radiation hardening of various hard working mechanical components (drill bits and boring tools). These useful applications of radiation effects are referred to as neutron processing.

All of these applications are possible owing to the absorption of neutrons. Neutrons are absorbed but also scattered from condensed matter. Neutron scattering has many applications as well; some of which are included. The field of neutron scattering uses thermal or cold neutrons as a diagnostic probe to investigate the structure, phase transitions and dynamics of a wide variety of materials. The popular technique of small-angle neutron scattering has received much use to investigate such practical applications. A few applications are described, such as wax buildup in diesel engines, the structure of hydrogen fuel cell membranes, the nanostructure characterization of various white marbles, the cleaning of masterpiece paintings and the mapping out of residual stress in engineering materials.

## BRIEF HISTORY

The early twentieth century was an era of intense scientific progress in the field of Physics. The neutron was discovered by Chadwick in 1932. Many charged particles were already known and x-rays had been discovered. The first charged particle accelerators had been built. Neutron applications started taking off. Neutrons get absorbed and scattered from nuclei inside matter. Neutron wavelengths are comparable to atomic sizes making them an ideal probe for investigating condensed matter. Their enhanced absorption cross section at long wavelengths (i.e, with “cold neutrons”) is the basis for many neutron applications.

In 1942, the first controlled nuclear fission reaction was demonstrated by Fermi’s team at the University of Chicago’s stadium. It was a simple pile containing natural uranium that was surrounded by graphite to moderate and reflect neutrons back; a sustained fission reaction was achieved.

An effort was undertaken during World War II by all sides (Germany, the Soviet Union and the United States) to build nuclear weapons. The United States started a huge effort referred to as the Manhattan Project at Oak Ridge (Tennessee) and Los Alamos (New Mexico) national labs to enrich the uranium isotope required to build a nuclear weapon (atomic bomb) based on the fission reaction. In 1945, the United States finished the construction of two nuclear weapons which were sadly used against Hiroshima and Nagasaki in August 1945. The names given to these weapons were “Fat Man” and “Little Boy”. The hydrogen bomb (based on the fusion nuclear reaction instead) came a few years later.

The technology for building linear charged particle accelerators kept improving, achieving higher kinetic energies for the accelerated protons (mostly). The first cyclotron (ring accelerator) was constructed in 1950. Cyclotrons (also called synchrotrons) can achieve much higher kinetic energies than linear accelerators because of the build-up at each revolution. The introduction of wigglers (magnetic fields that periodically steer the accelerated charged particles) helped produce intense coherent beams of x-rays.

In 1953, President Eisenhower launched the Atoms for Peace program thereby challenging the United States "to devote its entire heart and mind to find the way by which the miraculous inventiveness of man shall not be dedicated to his death (through the use of nuclear weapons) but consecrated to his life (through other uses of nuclear energy and other nuclear applications)."

The technology for building nuclear reactors advanced rapidly. Many research reactors were built at national labs in the United States (Argonne, Oak Ridge, Brookhaven, National Institute of Standards and Technology). Following the first one called CP1 (for Chicago Pile 1), CP2 to CP5 were constructed within a few years.

In 1955, the first university-based nuclear reactor was constructed at Penn State University. Many universities built research reactors in the late 1950s and during the 1960s. The US Atomic Energy Commission (AEC) built the High-Flux Isotope Reactor (100 MW) at Oak Ridge National Lab in order to produce radioisotopes. The AEC will later be renamed the Department of Energy (DOE). The name Phoenix was given to the University of Michigan research reactor (built in 1957) to symbolize the rebirth of nuclear science from its ashes.

The first neutron scattering experiments were conducted at Oak Ridge National Lab in the 1950s. X-ray scattering was already developed. With the advent of the laser in 1960, laser-light scattering will add to the panoply of scattering methods.

In the 1960s, the first power-producing nuclear reactors were built. These were mostly Pressurized Water Reactors (PWR) using enriched uranium (U-235) as fuel and water as moderator and coolant. Other reactor designs were introduced over the years. The best known are the Boiling Water Reactor (BWR), the Gas-Cooled Reactor (GCR), the CANDU (Canadian design using natural uranium), and the Fast Breeder Reactor (FBR) that uses the abundant uranium isotope U-238. The PWR design ended up dominating the field. The FBR uses liquid sodium as coolant and is therefore more prone to loss-of-coolant problems. The Superphoenix facility in France was an FBR and produced electricity commercially until 1996. Presently there is one commercial FBR operating in Russia.

In 1975, concept of the neutron-producing spallation source was demonstrated at the Argonne National Lab in Chicago (Illinois). This uses cyclotrons to accelerate charged particles (protons) which are then made to hit a high-Z target thereby releasing excess neutrons. In 1985, the first operating spallation source called the Intense Pulsed Neutron Source was opened to users at the Argonne National lab. The Los Alamos National Lab built another spallation source for weapons research and for neutron scattering.

In 1979, an accident at the Three Mile Island (power generating) nuclear reactor was caused by a loss of coolant which led to a core meltdown. This resulted in the release of substantial amount of radioactive products (mostly krypton gas but also iodine-131) to the surrounding area near Harrisburg, Pennsylvania. One post accident study reported no health effect on the population while another reported detectable increase of occurrences of lung cancer and leukemia as well as infant mortality downwind from the site.

In 1985, the first cold neutron source was installed at Brookhaven National Lab. Thermal neutrons (that slow down in the water moderator) have low kinetic energies (around 25 meV) corresponding to 1.8 Å wavelength. Cold neutrons (that are slowed down in liquid hydrogen) have even lower kinetic energies corresponding to wavelength higher than 5 Å. The speed of a thermal neutron is around 2200 m/s while that of a cold neutron with 5 Å wavelength is around 800 m/s.

Another nuclear reactor accident happened in 1986 at Chernobyl in northern Ukraine (part of the former Soviet Union at the time). A series of events led to a steam explosion

which blew up the confinement building thereby releasing huge amounts of radioactive gas. Four workers died and an entire evacuation of the immediate area was ordered a couple of days later. Many people suffered radioactive exposure. A radioactive cloud moved westward across many countries in Europe and was detectable as far west as France. The immediate area of Chernobyl was never repopulated.

In 1994, the Nobel Prize for Physics was awarded to two pioneer neutron scatterers (Brockhouse and Shull). In the mid 1990's a project to build the next generation research reactor (the Advanced Neutron Source) at Oak Ridge National Lab was cancelled due to budget constraints. DOE pulled the plug on that project when the cost escalated to over 3 billion dollars. It was replaced by a more cost-effective project; the Spallation Neutron Source which entered into operation in 2006. The new millennium brought about many upgrades of existing facilities as well as the construction of a few new ones. After a long drought, neutron science was finally doing well.

The term “nuclear” is often used negatively in the news media. Whether in connection with the above mentioned reactor accidents (Three Mile Island and Chernobyl), in connection with nuclear weapons buildup by superpowers or by rogue states or just in connection with radiation poisoning. For instance, in 2006, the story of the poisoning of a Russian dissident hit the evening news. Alexander Litvinenko was a former KGB agent that defected and was living in the United Kingdom. He was poisoned by eating food containing polonium-210 which killed him. Po-210 emits both beta and alpha particles that cause internal damage to the digestive track when ingested. This led him to a slow and agonizing death following internal organ failure.

Nuclear energy entered history through destructive nuclear weapons but has matured to the status of a beneficial means of helping humanity through a host of practical nuclear applications. These have found widespread uses in many areas including medicine, environmental, forensic science, art history, radioisotope applications as tracers as well as for the radiotherapy of cancers, in neutron gauging used in mining operations, the transmutation doping of silicon to produce semiconductors, the coloration of gemstones, as well as many other beneficial applications.

## ELEMENTS OF NUCLEAR PHYSICS

### ELEMENTARY PARTICLES

Atoms are formed of a nucleus surrounded by electrons orbiting it in different shells [1]. The atomic number  $Z$  represents the number of electrons in an atom.  $Z$  also represents the number of protons inside the nucleus. The nucleus contains protons and neutrons (called nucleons). Nucleons are much heavier than electrons (ratio of the two masses is around 1836). Atomic sizes are of order of angstroms ( $1 \text{ \AA} = 10^{-8} \text{ cm}$ ) while nuclear sizes are of order of fermis ( $1 \text{ Fm} = 10^{-13} \text{ cm}$ ). The atomic mass corresponds to the total number of nucleons ( $A = Z+N$ ); each nucleon weighing approximately one atomic mass unit (amu).

Electrons are also called beta ( $\beta$ ) particles. Helium nuclei are called alpha ( $\alpha$ ) particles. Positrons ( $\beta^+$ ) are of the same mass as electrons but have a positive charge (they are sometime referred to as anti-electrons). They are produced by the decay of positron emitters. Positrons get annihilated when they encounter electrons thereby producing two gamma rays. Each of these gamma rays has an energy of 0.511 MeV (energy-equivalent mass of an electron). Charged particles are easily stopped while gamma rays are highly penetrating. They get shielded against using high- $Z$  materials such as lead or bismuth.

### ATOMIC PHYSICS AND PERIODIC TABLE OF THE ELEMENTS

Electronic shells are filled sequentially with one electron for the hydrogen atom, and two for helium in the first (called K) shell. Lithium contains two electrons in the first shell and a third electron in the second (called L) shell. There is a specific order in filling electronic shells. Sub-shells are noted s, p, d, f, etc. These can contain up to 2, 6, 10, 14, etc, electrons respectively and correspond to orbital angular momentum numbers  $l = 0, 1, 2, 3$ , etc. The number of electrons in each sub-shell is  $2l+1$ .

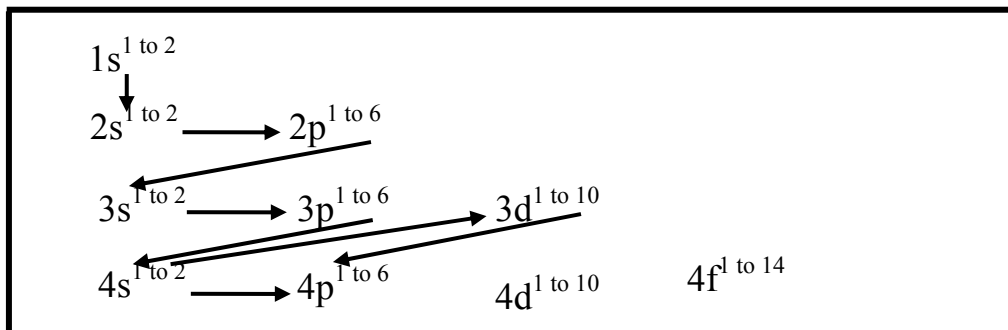


Figure 1: Sequence of filling up electronic shells.

Table 1: The first four electronic shells, their sub-shells and the corresponding elements.

H 1s <sup>1</sup>																	He 1s <sup>2</sup>
Li 2s <sup>1</sup>	Be 2s <sup>2</sup>											B 2p <sup>1</sup>	C 2p <sup>2</sup>	N 2p <sup>3</sup>	O 2p <sup>4</sup>	F 2p <sup>5</sup>	Ne 2p <sup>6</sup>
Na 3s <sup>1</sup>	Mg 3s <sup>2</sup>											Al 3p <sup>1</sup>	Si 3p <sup>2</sup>	P 3p <sup>3</sup>	S 3p <sup>4</sup>	Cl 3p <sup>5</sup>	Ar 3p <sup>6</sup>
K 4s <sup>1</sup>	Ca 4s <sup>1</sup>	Sc 3d <sup>1</sup>	Ti 3d <sup>2</sup>	V 3d <sup>3</sup>	Cr 3d <sup>4</sup>	Mn 3d <sup>5</sup>	Fe 3d <sup>6</sup>	Co 3d <sup>7</sup>	Ni 3d <sup>8</sup>	Cu 3d <sup>9</sup>	Zn 3d <sup>10</sup>	Ga 4p <sup>1</sup>	Ge 4p <sup>2</sup>	As 4p <sup>3</sup>	Se 4p <sup>4</sup>	Br 4p <sup>5</sup>	Kr 4p <sup>6</sup>

This scheme is kept up in order to fill the periodic table of the elements which was introduced by Mendeleev in 1920.

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**NIST**  
National Institute of Standards and Technology  
Technology Administration, U.S. Department of Commerce

**Frequently used fundamental physical constants**  
For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

speed of light in vacuum  $c$  299 792 458 m s<sup>-1</sup> (exact)  
Planck constant  $h$  6.626 070 15 × 10<sup>-34</sup> J s (exact) ( $h = h/2\pi$ )  
elementary charge  $e$  1.602 176 634 × 10<sup>-19</sup> C  
electron mass  $m_e$  9.109 383 56 × 10<sup>-31</sup> kg  
 $m_e c^2$  0.5110 MeV  
proton mass  $m_p$  1.672 621 63 × 10<sup>-27</sup> kg  
 $d$  1/137.036  
fine-structure constant  $\alpha$  10 973 732 m<sup>-1</sup>  
 $R_\infty c$  13 605 7 eV  
 $R_\infty h c$  13 605 7 eV  
Boltzmann constant  $k$  1.380 658 × 10<sup>-23</sup> J K<sup>-1</sup>

**Legend:**  
Solids (white)  
Liquids (light blue)  
Gases (light green)  
Artificially Prepared (yellow)

**Group 1 IA**  
1 H  
3 Li  
11 Na  
19 K  
37 Rb  
55 Cs  
87 Fr

**Group 2 IIA**  
4 Be  
12 Mg  
20 Ca  
38 Sr  
56 Ba  
88 Ra

**Group 3 IIIB**  
21 Sc  
39 Y  
57 La  
89 Ac

**Group 4 IVB**  
22 Ti  
40 Zr  
58 Ce  
90 Th

**Group 5 VB**  
23 V  
41 Nb  
59 Pr  
91 Pa

**Group 6 VIB**  
24 Cr  
42 Mo  
60 Nd  
92 U

**Group 7 VIIB**  
25 Mn  
43 Tc  
61 Pm  
93 Np

**Group 8 VIII**  
26 Fe  
44 Ru  
62 Sm  
94 Pu

**Group 9 VIII**  
27 Co  
45 Rh  
63 Eu  
95 Am

**Group 10 VIII**  
28 Ni  
46 Pd  
64 Gd  
96 Cm

**Group 11 IB**  
29 Cu  
47 Ag  
65 Tb  
97 Bk

**Group 12 IIB**  
30 Zn  
48 Cd  
66 Dy  
98 Cf

**Group 13 IIIA**  
5 B  
13 Al  
31 Ga  
49 In  
67 Ho  
85 At

**Group 14 IVA**  
6 C  
14 Si  
32 Ge  
50 Sn  
68 Er  
86 Rn

**Group 15 VA**  
7 N  
15 P  
33 As  
51 Sb  
69 Tm  
87 Lu

**Group 16 VIA**  
8 O  
16 S  
34 Se  
52 Te  
70 Yb  
88 Ra

**Group 17 VIIA**  
9 F  
17 Cl  
35 Br  
53 I  
71 Lu  
89 Ac

**Group 18 VIIIA**  
10 Ne  
18 Ar  
36 Kr  
54 Xe  
72 Hf  
90 Th

**Group 19 VIIIA**  
11 Na  
19 K  
37 Rb  
55 Cs  
87 Fr

**Group 20 VIIIA**  
12 Mg  
20 Ca  
38 Sr  
56 Ba  
88 Ra

**Group 21 VIIIA**  
21 Sc  
39 Y  
57 La  
89 Ac

**Group 22 VIIIA**  
22 Ti  
40 Zr  
58 Ce  
90 Th

**Group 23 VIIIA**  
23 V  
41 Nb  
59 Pr  
91 Pa

**Group 24 VIIIA**  
24 Cr  
42 Mo  
60 Nd  
92 U

**Group 25 VIIIA**  
25 Mn  
43 Tc  
61 Pm  
93 Np

**Group 26 VIIIA**  
26 Fe  
44 Ru  
62 Sm  
94 Pu

**Group 27 VIIIA**  
27 Co  
45 Rh  
63 Eu  
95 Am

**Group 28 VIIIA**  
28 Ni  
46 Pd  
64 Gd  
96 Cm

**Group 29 VIIIA**  
29 Cu  
47 Ag  
65 Tb  
97 Bk

**Group 30 VIIIA**  
30 Zn  
48 Cd  
66 Dy  
98 Cf

**Group 31 VIIIA**  
31 Ga  
49 In  
67 Ho  
85 At

**Group 32 VIIIA**  
32 Ge  
50 Sn  
68 Er  
86 Rn

**Group 33 VIIIA**  
33 As  
51 Sb  
69 Tm  
87 Lu

**Group 34 VIIIA**  
34 Se  
52 Te  
70 Yb  
88 Ra

**Group 35 VIIIA**  
35 Br  
53 I  
71 Lu  
89 Ac

**Group 36 VIIIA**  
36 Kr  
54 Xe  
72 Hf  
90 Th

**Group 37 VIIIA**  
37 Rb  
55 Cs  
87 Fr

**Group 38 VIIIA**  
38 Sr  
56 Ba  
88 Ra

**Group 39 VIIIA**  
39 Y  
57 La  
89 Ac

**Group 40 VIIIA**  
40 Zr  
58 Ce  
90 Th

**Group 41 VIIIA**  
41 Nb  
59 Pr  
91 Pa

**Group 42 VIIIA**  
42 Mo  
60 Nd  
92 U

**Group 43 VIIIA**  
43 Tc  
61 Pm  
93 Np

**Group 44 VIIIA**  
44 Ru  
62 Sm  
94 Pu

**Group 45 VIIIA**  
45 Rh  
63 Eu  
95 Am

**Group 46 VIIIA**  
46 Pd  
64 Gd  
96 Cm

**Group 47 VIIIA**  
47 Ag  
65 Tb  
97 Bk

**Group 48 VIIIA**  
48 Cd  
66 Dy  
98 Cf

**Group 49 VIIIA**  
49 In  
67 Ho  
85 At

**Group 50 VIIIA**  
50 Sn  
68 Er  
86 Rn

**Group 51 VIIIA**  
51 Sb  
69 Tm  
87 Lu

**Group 52 VIIIA**  
52 Te  
70 Yb  
88 Ra

**Group 53 VIIIA**  
53 I  
71 Lu  
89 Ac

**Group 54 VIIIA**  
54 Xe  
72 Hf  
90 Th

**Group 55 VIIIA**  
55 Cs  
87 Fr

**Group 56 VIIIA**  
56 Ba  
88 Ra

**Group 57 VIIIA**  
57 La  
89 Ac

**Group 58 VIIIA**  
58 Ce  
90 Th

**Group 59 VIIIA**  
59 Pr  
91 Pa

**Group 60 VIIIA**  
60 Nd  
92 U

**Group 61 VIIIA**  
61 Pm  
93 Np

**Group 62 VIIIA**  
62 Sm  
94 Pu

**Group 63 VIIIA**  
63 Eu  
95 Am

**Group 64 VIIIA**  
64 Gd  
96 Cm

**Group 65 VIIIA**  
65 Tb  
97 Bk

**Group 66 VIIIA**  
66 Dy  
98 Cf

**Group 67 VIIIA**  
67 Ho  
85 At

**Group 68 VIIIA**  
68 Er  
86 Rn

**Group 69 VIIIA**  
69 Tm  
87 Lu

**Group 70 VIIIA**  
70 Yb  
88 Ra

**Group 71 VIIIA**  
71 Lu  
89 Ac

**Group 72 VIIIA**  
72 Hf  
90 Th

**Group 73 VIIIA**  
73 Ta  
91 Pa

**Group 74 VIIIA**  
74 W  
92 U

**Group 75 VIIIA**  
75 Re  
93 Np

**Group 76 VIIIA**  
76 Os  
94 Pu

**Group 77 VIIIA**  
77 Ir  
95 Am

**Group 78 VIIIA**  
78 Pt  
96 Cm

**Group 79 VIIIA**  
79 Au  
97 Bk

**Group 80 VIIIA**  
80 Hg  
98 Cf

**Group 81 VIIIA**  
81 Tl  
99 Es

**Group 82 VIIIA**  
82 Pb  
100 Fm

**Group 83 VIIIA**  
83 Bi  
101 Md

**Group 84 VIIIA**  
84 Po  
102 No

**Group 85 VIIIA**  
85 At  
103 Lr

**Group 86 VIIIA**  
86 Rn

**Group 87 VIIIA**  
87 Fr

**Group 88 VIIIA**  
88 Ra

**Group 89 VIIIA**  
89 Ac

**Group 90 VIIIA**  
90 Th

**Group 91 VIIIA**  
91 Pa

**Group 92 VIIIA**  
92 U

**Group 93 VIIIA**  
93 Np

**Group 94 VIIIA**  
94 Pu

**Group 95 VIIIA**  
95 Am

**Group 96 VIIIA**  
96 Cm

**Group 97 VIIIA**  
97 Bk

**Group 98 VIIIA**  
98 Cf

**Group 99 VIIIA**  
99 Es

**Group 100 VIIIA**  
100 Fm

**Group 101 VIIIA**  
101 Md

**Group 102 VIIIA**  
102 No

**Group 103 VIIIA**  
103 Lr

**Group 104 VIIIA**  
104 Rf

**Group 105 VIIIA**  
105 Db

**Group 106 VIIIA**  
106 Sg

**Group 107 VIIIA**  
107 Bh

**Group 108 VIIIA**  
108 Hs

**Group 109 VIIIA**  
109 Mt

**Group 110 VIIIA**  
110 Uun

**Group 111 VIIIA**  
111 Uuu

**Group 112 VIIIA**  
112 Uub

**Group 113 VIIIA**  
113 Uuq

**Group 114 VIIIA**  
114 Uuq

**Group 115 VIIIA**  
115 Uuh

**Group 116 VIIIA**  
116 Uuh

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117 Uuh

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**Group 134 VIIIA**  
134 Uuh

**Group 135 VIIIA**  
135 Uuh

**Group 136 VIIIA**  
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electron and can therefore form one covalent bond; carbon has two paired ( $2p^2$ ) and four unpaired electrons in the outer (second) shell and can therefore form four covalent bonds. Oxygen can form two single bonds, etc. Double bonds (such as in  $-C=C-$ ) involve the pairing of two electrons in each of the two atoms. The entire field of chemistry is based on understanding the covalent bonding necessary to form molecules through chemical reactions.

Atoms are excited when electrons jump to higher energy levels (i.e., to higher shells). Excited atoms decay by emitting light. Excitation energies for atomic transitions are in the eV to keV range. For example, the hydrogen atom's lowest excitation energy is around 10 eV. Note that  $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} = 3.832 \times 10^{-20} \text{ cal}$ . The visible range of emitted light corresponds to wavelengths between  $0.4 \mu\text{m}$  (blue light) and  $0.7 \mu\text{m}$  (red light). Large atoms have many electronic shells and therefore are characterized by large excitation/decay energies in the x-ray range (of order keV). Various spectroscopic methods measure the absorption/emission of light in the various spectral ranges.

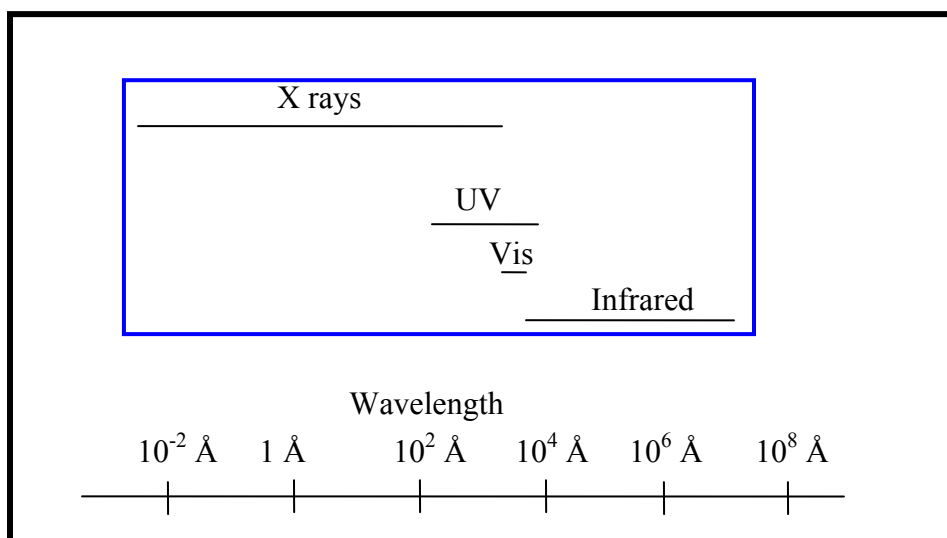


Figure 3: Spectral ranges of various electromagnetic radiations.

## THE NUCLEUS

The nucleus is formed of neutrons and protons and is at the heart of the atom [2]. It is also characterized by energy levels for nuclear transitions; these however, correspond to larger energies (in the MeV range). Note that  $1 \text{ MeV} = 10^6 \text{ eV}$ . The atomic mass unit (amu) corresponds to the energy of 931 MeV. This is the  $E = mc^2$  nuclear energy (where  $m$  is the mass and  $c$  is the speed of light) introduced by Einstein. The proton mass corresponds to 938 MeV while the neutron mass is 1.3 MeV heavier.

Radioactive elements are produced through neutron irradiation (inside a nuclear reactor) or using particle accelerators (linear accelerators or cyclotrons). Note that gamma ( $\gamma$ ) rays

are photons just like x-rays and light. Photons travel at the speed of light and have no mass. Gamma rays are emitted through nuclear transitions while x-rays and light are emitted through atomic transitions. Note that electronic transitions emit one photon with energy equal to the transition energy while nuclear transitions emit gamma rays over a period of time till the energy absorbed by the nucleus is exhausted. For example, the absorption of a neutron is equivalent to a total energy of 939.3 MeV.

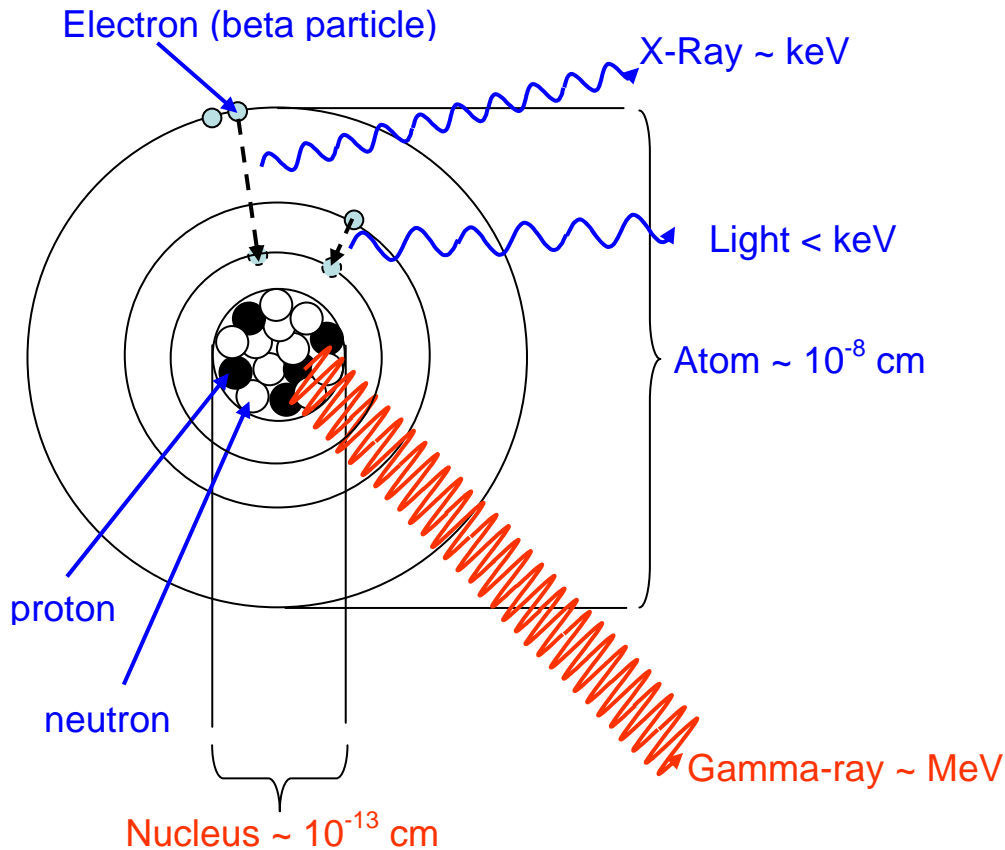


Figure 4: Schematics of atomic and nuclear transitions.

## NUCLEI WITH EXCESS NEUTRONS

The neutron decays into a proton, an electron and an antineutrino [3] with a half-life of 894 seconds (about 15 minutes). Neutron decay is observed by trapping free neutrons inside a magnetic “bottle” and monitoring the emission of protons and electrons in coincidence. Neutrons decay only when forming radioisotope nuclei; they do not decay when bound inside stable nuclei.

Neutrinos and antineutrinos are neutral particles with very small mass that travel with speeds close to the speed of light; they are very difficult to detect. Unbound protons are stable; their hypothesized decay into pi-mesons (also called pions) and positrons has never been observed. Mesons are sub-nuclear particles.

Stable nuclei tend to have an excess of neutrons (more neutrons than protons). Nuclei with high excess neutrons tend to be beta emitters while those with low excess neutrons tend to be positron emitters. Heavy nuclei tend to be alpha emitters [4].

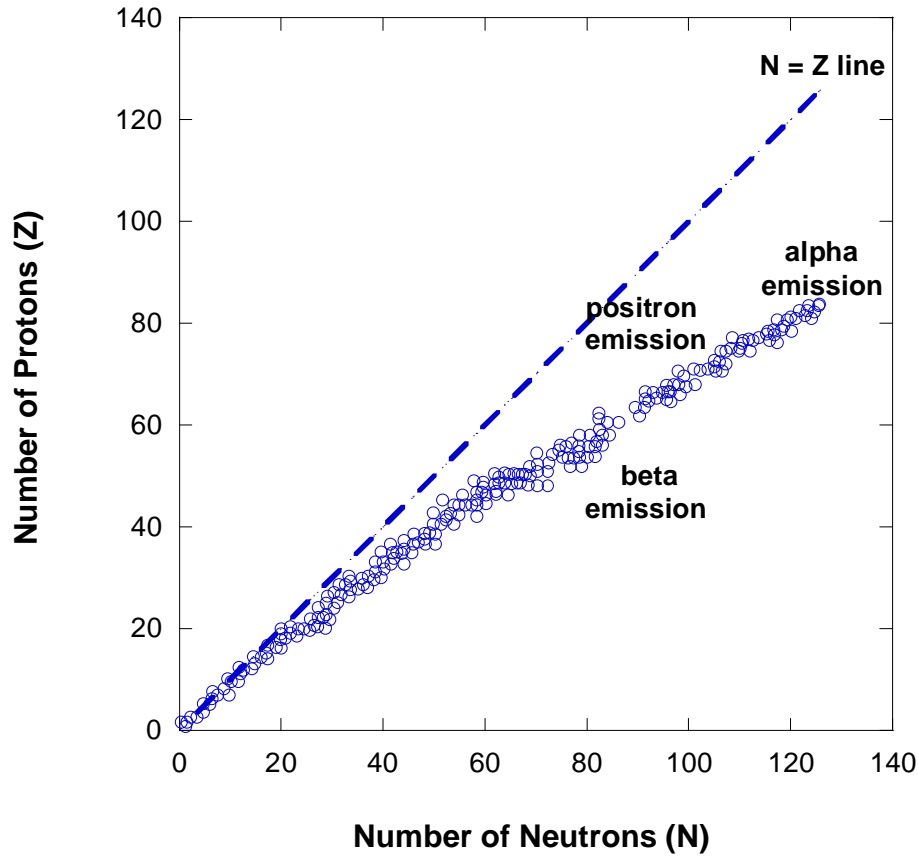
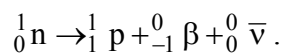


Figure 5: Points represent stable elements. Radioactive decay occurs above and below this band of stable elements.

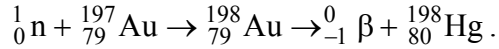
## NUCLIDES AND ISOTOPES

The three main decay schemes (by beta, positron and alpha emissions) and the electron capture scheme are described here.

Beta emission is produced by the following neutron conversion reaction in neutron-rich nuclei whereby a neutron yields a proton, a beta particle and an antineutrino:

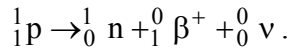


An example of the production and decay reactions of a beta emitter follows:



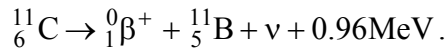
The familiar notation for a nucleus M with atomic number Z and atomic mass A as  ${}_Z^A\text{M}$  is followed [5]. Note that A and Z must be conserved on each side of the nuclear reaction. Sometime the number of neutrons  $N = A - Z$  is also included as in  ${}_Z^A\text{M}_N$ .

Positron emission is produced by the following bound proton conversion reaction in proton-rich (or neutron poor) nuclei:

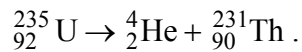


Note that this type of conversion does not occur for free (i.e., unbound) protons but only inside nuclei. Since a proton is lighter than the neutron plus positron pair (by  $1.3\text{ MeV} + 0.511\text{ MeV} = 1.8\text{ MeV}$ ) additional energy is required to produce positrons. Whereas beta emitters are produced in nuclear reactors, positron emitters are produced mostly using particle accelerators. Some are also produced using nuclear reactors.

An example of the decay of a positron emitter follows the reaction:



Some heavy nuclei emit alpha particles ( ${}_2^4\text{He}$  nuclei). An example of the decay of an alpha emitter follows the reaction:



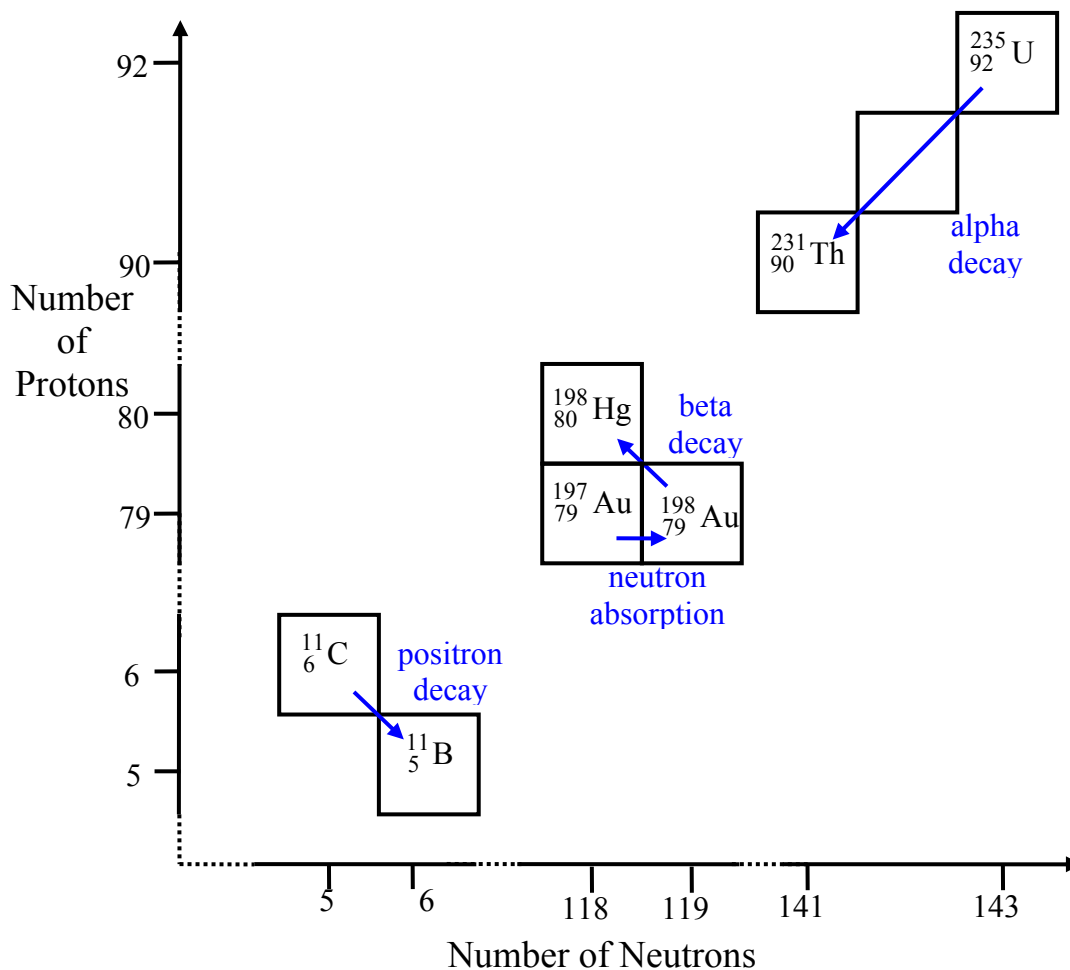


Figure 6: Examples of a beta, a positron and an alpha emission schemes.

When not enough excess energy is available to emit a positron, the conversion of a proton to a neutron occurs through the capture of an orbiting electron by the nucleus. The captured electron leaves an empty electronic slot in the low lying atomic K shell. This slot gets filled by another electron decaying from a higher orbital thereby releasing an x-ray. Sometime, instead of releasing an x-ray, another (called Auger) electron is knocked out of its electronic shell and becomes free. Electron capture does not occur in fully ionized atoms.

Some nuclei undergo more than one mode of decay. For example,  $^{64}_{29}\text{Cu}$  is produced at a nuclear reactor as well as using charged particle accelerators. It has a half-life of 12.7 years and decays by beta emission, by positron emission and by electron capture.

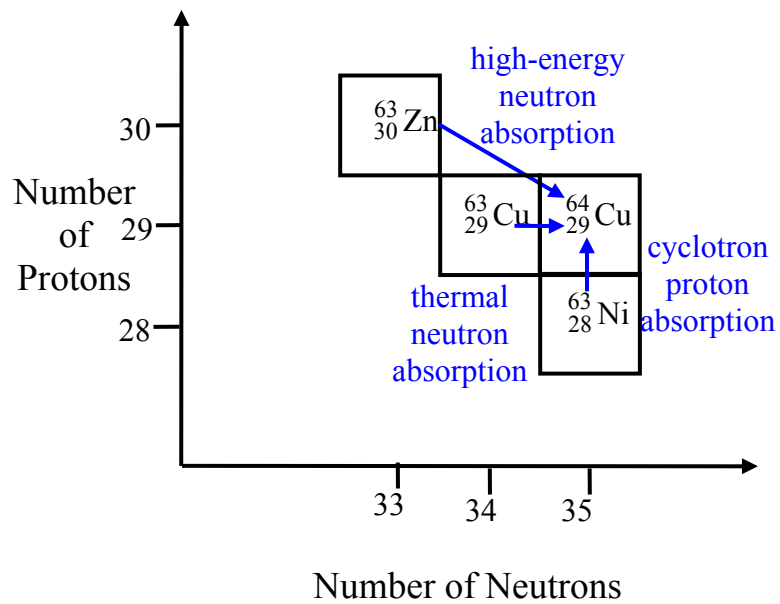


Figure 7: Production schemes for  $^{64}_{29}\text{Cu}$ .

Table 2: Decay schemes for  $^{64}_{29}\text{Cu}$

Reaction	Decay type	Probability
$^{64}_{29}\text{Cu} \rightarrow ^0_{-1}\beta + ^{64}_{30}\text{Zn}$	Beta decay	39 %
$^{64}_{29}\text{Cu} \rightarrow ^0_1\beta^+ + ^{64}_{28}\text{Ni}$	Positron decay	18 %
$^{64}_{29}\text{Cu} + ^0_{-1}\beta \rightarrow ^{64}_{28}\text{Ni}$	Electron capture	43 %

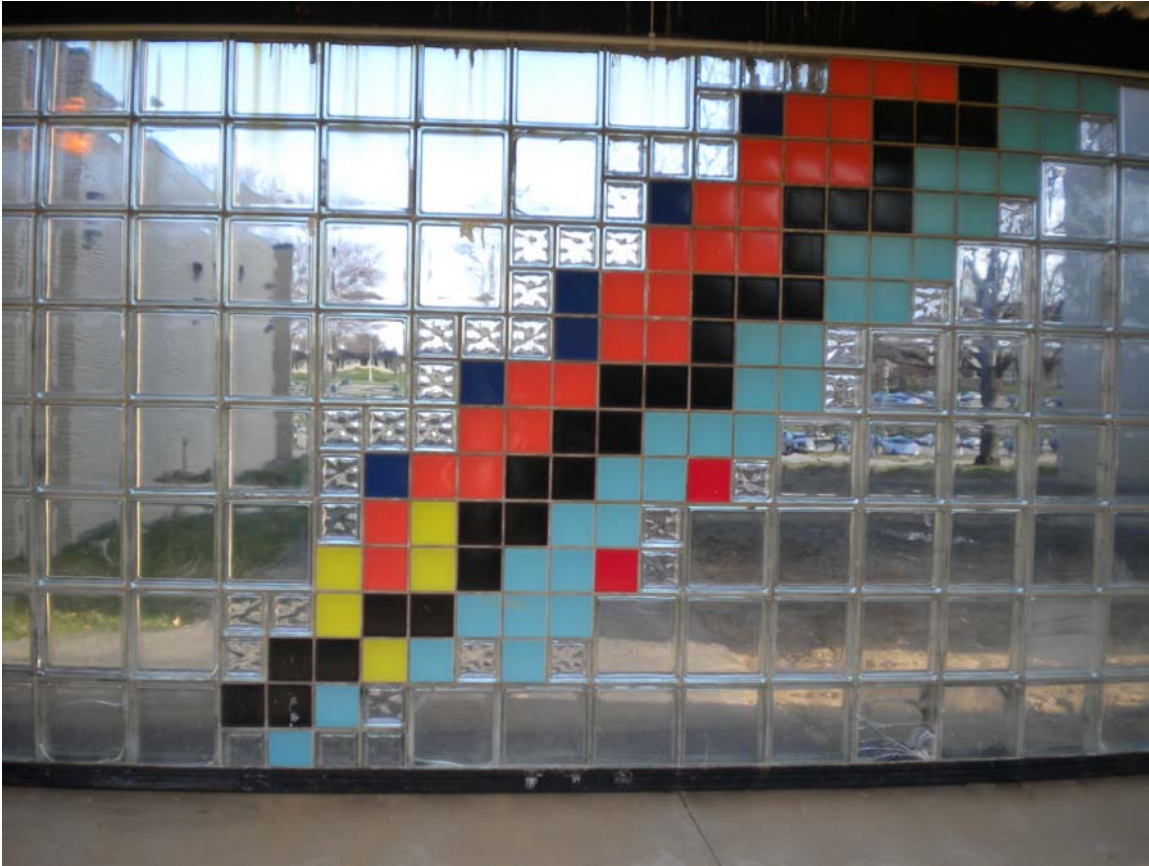


Figure 8: Photo of the walkway area behind the Radiation Physics building at the National Institute of Standards and Technology. The tiles represent the low- $Z$  stable elements in black, positron emitters in blue and beta emitters in red. The horizontal axis is the number of protons and the vertical axis is the number of neutrons. Note that the Chart of the Nuclides (followed here) uses the other convention.

Nuclear reactions involving the transmutation of an element into another are referred to as “isobaric” transitions. Isobaric transitions are accompanied by the emission of a charged particle (such as an electron, a positron or an alpha particle) or by electron capture. They involve different squares for the initial and final products in the  $N/Z$  chart of the nuclides. Isobaric transitions often lead to excited (metastable) states that decay to the ground state by emitting gamma rays. Such decay transitions (involving the same square) are referred to as isomeric transitions. Most nuclear reactions are accompanied by gamma emission.

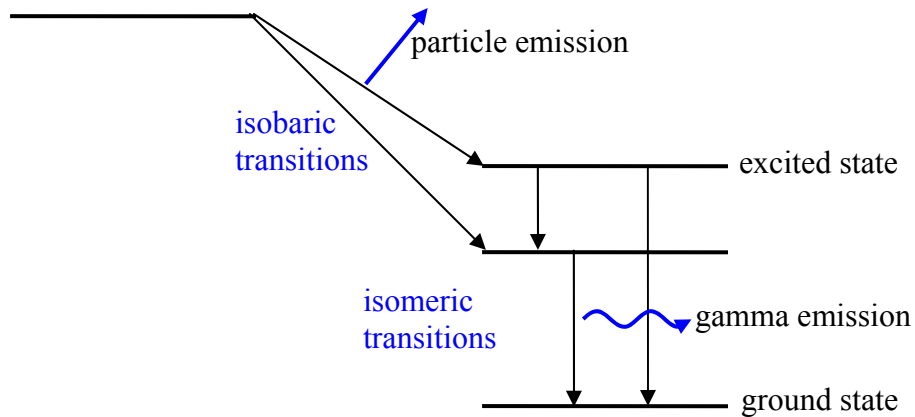
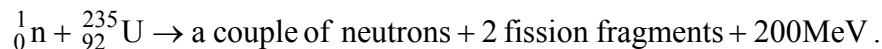


Figure 9: Isobaric transitions produce particles while isomeric transitions produce gamma rays.

Instead of emitting a gamma ray, isomeric transitions can sometime knock an atomic electron out of its orbiting shell through what is called “internal conversion”.

## A FEW NUCLEAR REACTIONS OF INTEREST

A few nuclear reactions are described here. The fission reaction involves many fissile nuclei. The best known is U-235.

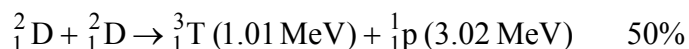


The U-235 isotope is not abundant (only 0.7 %) in natural uranium. The enrichment process is technologically very complex. Fission is used in nuclear reactors as well as in nuclear weapons (atomic bombs). Fission produces a couple of neutrons to sustain the chain reaction. Splitting of U-235 produces two high-Z nuclei (fission fragments) with broad mass distributions peaked around  $A = 95$  and  $A = 140$ .

Fusion consists in fusing together light nuclei to produce heavier ones. One of the fusion reactions is as follows.

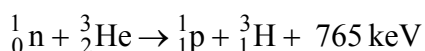


Detecting 14.1 MeV neutrons is the signature that this fusion reaction is taking place. Another fusion reaction can occur in the two following ways.



Tremendous amounts of energy are required to fuse nuclei together in order to overcome repulsive interactions between protons. Sustained fusion has been achieved in the laboratory using either strong magnetic fields in Tokamaks or inertial confinement using powerful lasers to achieve breakeven (for which as much energy is released as is used to compress the nuclei). Nuclear fusion, however, has not been viable for use at a large scale. Nuclear fusion has also been achieved in the hydrogen bomb (which should really be called the deuterium bomb). Note that an atomic bomb is needed to compress deuterium to the ignition point in a hydrogen bomb. Fusion is also the source of energy in the sun and other stars. Tremendous gravitational forces compress low-Z nuclei that fuse into heavier (and heavier) ones thereby releasing tremendous amounts of energy over billions of years. Most elements in the universe were made by fusion in stars. The most abundant element is iron since the fusion reaction making iron is the last exothermic reaction. Reactions to make heavier elements are endothermic.

Most neutron detectors use the following nuclear reaction involving the emission of a proton and a triton (tritium nucleus):



The two charged particles are attracted by the anode's high voltage wire thereby creating a detection cloud which gets sensed by the cathode.

A list of production and decay reactions of a few beta emitters follows. Parent and daughter isotopes are shown for the beta decay.

Table 3: Examples of beta emitters and their use

Production reaction	Decay reaction	Beta energy	Half-life	Radioisotope use
${}_0^1\text{n} + {}_{79}^{197}\text{Au} \rightarrow {}_{79}^{198}\text{Au}$	${}_{79}^{198}\text{Au} \rightarrow {}_{-1}^0\beta + {}_{80}^{198}\text{Hg}$	1.372 MeV	2.69 days	Radiotracer
${}_0^1\text{n} + {}_{53}^{124}\text{I} \rightarrow {}_{53}^{125}\text{I}$	${}_{53}^{125}\text{I} \rightarrow {}_{-1}^0\beta + {}_{54}^{125}\text{Xe}$	0.186 MeV	59.408 days	Lexiscope
${}_0^1\text{n} + {}_{28}^{62}\text{Ni} \rightarrow {}_{28}^{63}\text{Ni}$	${}_{28}^{63}\text{Ni} \rightarrow {}_{-1}^0\beta + {}_{29}^{63}\text{Cu}$	0.067 MeV	100 years	Smoke detector
${}_0^1\text{n} + {}_{27}^{59}\text{Co} \rightarrow {}_{27}^{60}\text{Co}$	${}_{27}^{60}\text{Co} \rightarrow {}_{-1}^0\beta + {}_{28}^{60}\text{Ni}$	2.824 MeV	5.285 years	Food irradiation
${}_0^1\text{n} + {}_{14}^{30}\text{Si} \rightarrow {}_{14}^{31}\text{Si}$	${}_{14}^{31}\text{Si} \rightarrow {}_{-1}^0\beta + {}_{15}^{31}\text{P}$	1.492 MeV	153 minutes	Transmutation doping

Table 4: Examples of positron emitters and their use

Production reaction	Decay reaction	Target Material	Positron energy	Half-life	Radioisotope use
${}_1^1\text{p} + {}_7^{14}\text{N} \rightarrow {}_2^4\text{He} + {}_6^{11}\text{C}$	${}_6^{11}\text{C} \rightarrow {}_1^0\beta^+ + {}_5^{11}\text{B}$	N <sub>2</sub> gas	386 keV	20	Radiotracer

				minutes	
${}^4_2\text{He} + {}^{16}_8\text{O} \rightarrow {}^1_1\text{p} + {}^1_0\text{n} + {}^{18}_9\text{F}$	${}^{18}_9\text{F} \rightarrow {}^0_1\beta^+ + {}^{18}_8\text{O}$	$\text{H}_2\text{O}$ ice	250 keV	110 minutes	Radiotracer

## RADIATION DETECTORS

There are three types of radiation detectors: charged particle counters, photon detectors and neutron detectors. Geiger counters detect charged particles (beta particles mostly). Since beta particles (electrons) are easily stopped, the Geiger counter has a very thin window and a characteristic grid to protect this thin window. It uses a tube filled with inert gas (such as helium, neon or argon) with halogens added. This gas mixture ionizes when ionizing radiation (either an energetic beta particle or a gamma ray) crosses it thereby producing an electrical pulse. A needle and audible clicks record detected events.

Geiger counters can detect beta particles as well as gamma rays. Gamma detectors use scintillation crystals (NaI), semiconductor materials (SiLi) or high purity germanium (Ge) as detection materials. The sodium iodide (NaI) scintillation counter for example, is used for dose rate measurements. Scintillators produce light which is converted to an electrical signal using the photoelectric effect. Some of these gamma detectors require cooling to liquid nitrogen temperature (77 K) in order to increase their efficiency.

Ionization chambers use high voltage between two electrodes in order to produce an electrical current each time the active detection gas is ionized. They produce an electrical output which is proportional to the radiation dose. Note that the Geiger counter detects radiation but cannot be used for radiation dose measurements.

Neutrons can be better detected when they are slowed down. The absorption cross section of most materials varies like  $1/v$  where  $v$  is the neutron speed (i.e., are  $1/v$  absorbers). A Bonner sphere uses hydrogen-containing material to slow down neutrons to thermal energies before they can be detected. A neutron detector (located at the core of the sphere) uses the  $\text{He-3}(n,p)\text{H-3}$  nuclear reaction to detect neutrons whereby a thermal neutron is absorbed in He-3 and produces a proton and a triton (tritium nucleus) H-3 which are charged and therefore ionize a stop gas. An electrical pulse is then sensed by the cathode.



Figure 10: Geiger counter used to detect beta particles (left) and special Geiger counter used to detect gamma radiation (right). A pancake Geiger counter is also used to detect ionizing radiation (beta particles and gamma rays) and has a visible grid to protect the thin window.



Figure 11: The pocket ionization chamber dosimeter (left). A whole body counter detects mostly gamma radiation over a large surface area (middle). The Bonner sphere slows down neutrons before detecting them (right).

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## NEUTRON SOURCES

Neutron sources are based on two main nuclear reactions: the fission and the spallation processes. Both use heavy nuclei that contain excess neutrons. Fission uses thermal neutrons to trigger the release of a couple of excess neutrons while spallation uses incident high energy protons to release a larger number of excess neutrons. Continuous reactors operate in a continuous neutron generation mode whereas spallation sources function in a pulsed (or time-of-flight) mode. Nuclear reactors constitute the majority of neutron sources; they use the fission process. The highest fluxes available are around a few  $\times 10^{15}$  n/cm<sup>2</sup>sec. Neutron sources are used for neutron irradiation as well as neutron scattering. Other minor methods of producing neutrons are discussed.

## NUCLEAR FISSION REACTORS

Most nuclear reactors use the uranium (U) fuel cycle at varying levels of enrichment of the fissile isotope (U-235). Natural U contains 0.7 % U-235. Low (<20 %), medium (20 to 50 %) or high (>90 %) fuel enrichment levels are used in nuclear research reactors. Power producing reactors use low (2 to 5 %) enrichment levels.

The fission reaction releases large amount of energy (200 MeV) as the U-235 nucleus splits into two fission fragments [1]. The fission fragments remain in the fuel elements making them highly radioactive and produce heat that must be removed through forced-flow water cooling. Energetic gamma rays and a couple of fast neutrons are also released. After being slowed down by the moderator material (usually light or heavy water) neutrons are used to sustain the fission reaction as well as in beam tubes for neutron scattering. Fission neutrons are produced with kinetic energies around 2 MeV and are then slowed down to thermal energies around 25 meV (note that 1 meV =  $10^{-6}$  eV). A reflector blanket (heavy water, beryllium, graphite) surrounds the reactor core to keep thermal neutrons from escaping.

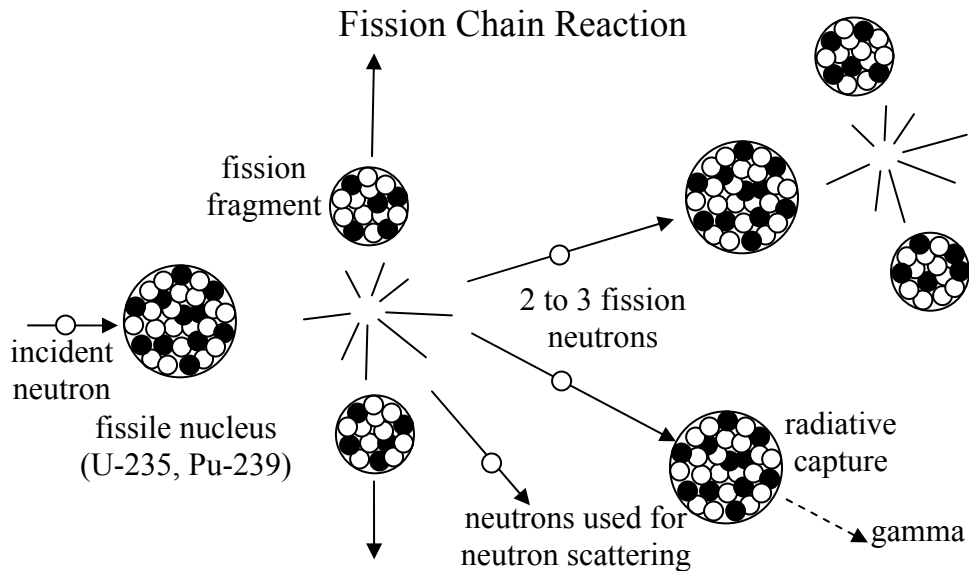


Figure 1: Typical fission chain reaction.

There are some 280 nuclear research reactors in the world most of which are located in highly developed countries [2]. They are used for irradiation, material testing and neutron scattering. The power of research reactors (up to 100 MW) is much lower than electrical power-producing reactors (>1000 MW). There are many designs for research reactors. These have compact cores and high fuel enrichment while power-producing reactors have extended (large) cores and low fuel enrichment. The former are used to produce intense radiation while the latter are used to produce lots of heat (i.e., generate power).

Most fission neutrons appear instantaneously during the fission event, and are called "prompt" neutrons. Less than 1 % of the neutrons appear after an appreciable delay time because they are emitted following the subsequent decay of radioactive fission products. Although these "delayed" neutrons are a very small fraction of the neutron population, these are vital to the operation of nuclear reactors and to the effective control of the nuclear chain reaction by "slowing" the transient kinetics. Put in simpler words, if these delayed neutrons did not exist, the neutron population would grow so fast following a small increase in reactivity that it would be impossible to operate a reactor safely. This is truly a gift of nature.

The Light Water Reactor (LWR) is the primary design used for fission reactors. For power production, the LWR uses water as moderator as well as coolant either in the pressurized form (Pressurized Water Reactor) or allowing it to boil (Boiling Water Reactor). Hydrogen in water is very effective at transferring kinetic energy from the thermalizing neutrons to the coolant which heats up. For large research reactors, forced water circulation (at several thousands of gallons per minute) helps remove the heat produced by fission from the primary coolant loop. This heat is then transferred to a secondary coolant loop through heat exchangers. A cooling tower usually helps cool down the secondary coolant before recirculation.



Figure 2: View of the reactor core at the University of Missouri Research Reactor. This is a light water pool reactor. The blue glow is due to Cerenkov radiation characteristic of the decay of fission fragments (beta emission). Beta particles are electrons.

Irradiations are performed in the core, reflector or beam tube regions. Irradiated materials are either directly placed in these regions or sent there from surrounding laboratories using pneumatic or hydraulic tubes. Neutron scattering is performed using beam tubes or neutron guides that help carry neutrons through long distances with minimal loss. Cold neutron sources (located in the reflector region) use liquid hydrogen (temperature around 20 K) to cool down thermal neutrons (25 meV) further and produce cold neutrons (kinetic energies lower than 4 meV). Cold neutrons (characterized by slower speeds and therefore longer wavelengths) are used for high resolution neutron scattering.

A short list of research reactors in the USA follows:

- HFIR-Oak Ridge National Laboratory (100 MW).
- NIST-The National Institute of Standards and Technology (20 MW).
- MURR-University of Missouri Research Reactor (10 MW).

These reactors were built during the 1960's but have undergone various upgrades.

There is one major research reactor in Canada:

- CRNL-Chalk River, Canada (135 MW).

A short list of research reactors in Europe follows:

- ILL-Grenoble, France (57 MW),
- NERF-Petten, Netherland (45 MW),
- FRM-II Munich, Germany (20 MW),
- KFKI-Budapest, Hungary (15 MW),
- LLB-Saclay, France (14 MW),
- HMI-Berlin, Germany (10 MW),
- Riso-Roskilde, Denmark (10 MW),
- VVR-M Leningrad, Russia (10 MW),
- GKSS Geesthacht, Germany (5 MW).

A short list of research reactors in Asia follows:

- DRHUVA-Bombay, India (100 MW),
- CIAE-Beijing, China (60 MW),
- NLHEP-Tsukuba, Japan (50 MW),
- Bhabha ARC-Bombay, India (40 MW),
- HFANAR, KAERI, Hanaro, Korea (30 MW)
- JRR3-Tokai Mura, Japan (20 MW),
- HWRR-Chengdo, China (15 MW),

One research reactor exists in Australia. ANSTO (20 MW) is located at the Bragg Institute.

## **THE NIST NEUTRON SOURCE**

The NIST Center for Neutron Research (CNR) operates a 20 MW research reactor that uses heavy water as moderator and coolant and has split-core fuel geometry. The heavy water and core geometry maximize the thermal neutron flux in the beam tubes. A liquid hydrogen cold source is used as a remoderator to produce cold neutrons. A set of neutron guides transport cold neutrons to a guide hall that contains a range of cold neutron scattering instruments. Thermal neutron scattering instruments are located inside the confinement building.

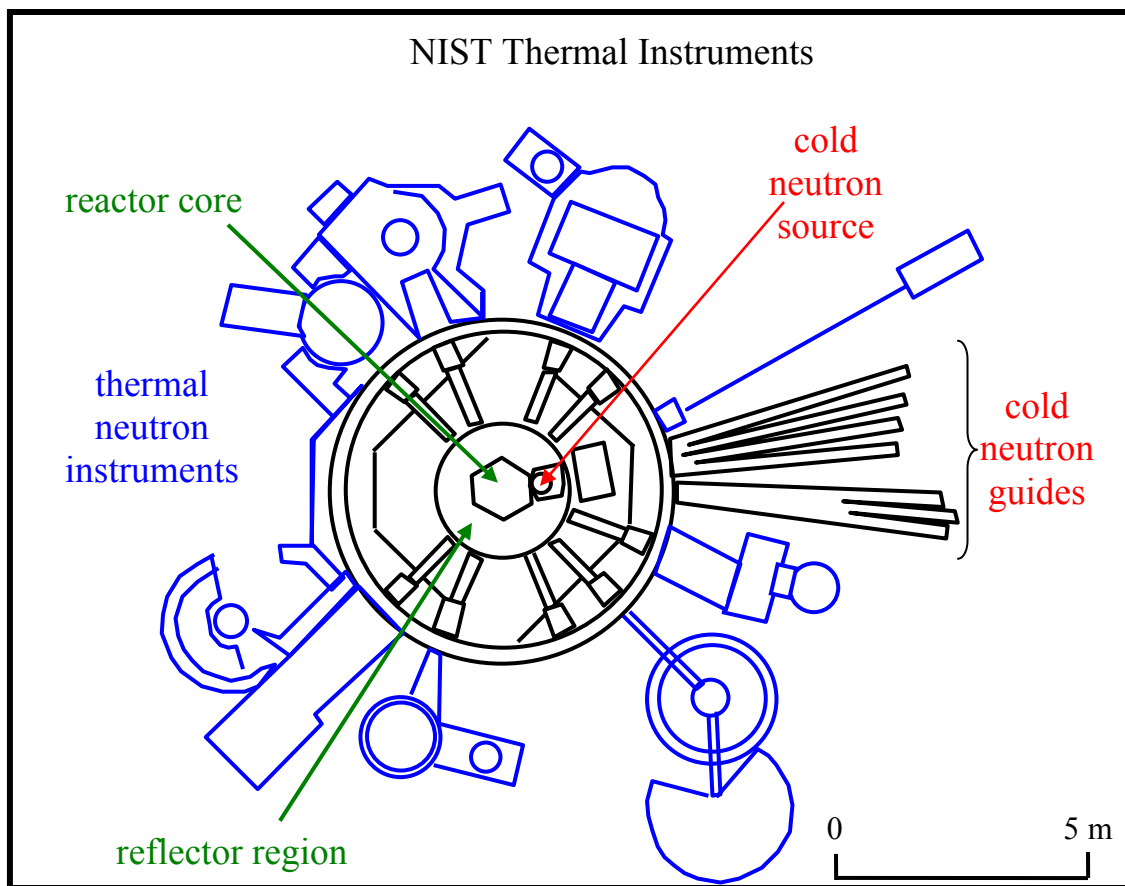


Figure 3: Schematics of the NIST confinement building showing the thermal neutron scattering instruments and the cold neutron source along with the beginning of the cold neutron guides leading to the current guide hall.

The NIST CNR current guide hall contains a set of seven guides looking at the cold source. Cold neutron instruments include SANS instruments, reflectometers, a time-of-flight instrument, a cold triple axis, a backscattering spectrometer, a neutron spin-echo spectrometer and other fundamental physics stations (interferometry, measurement of the neutron half-life, etc).

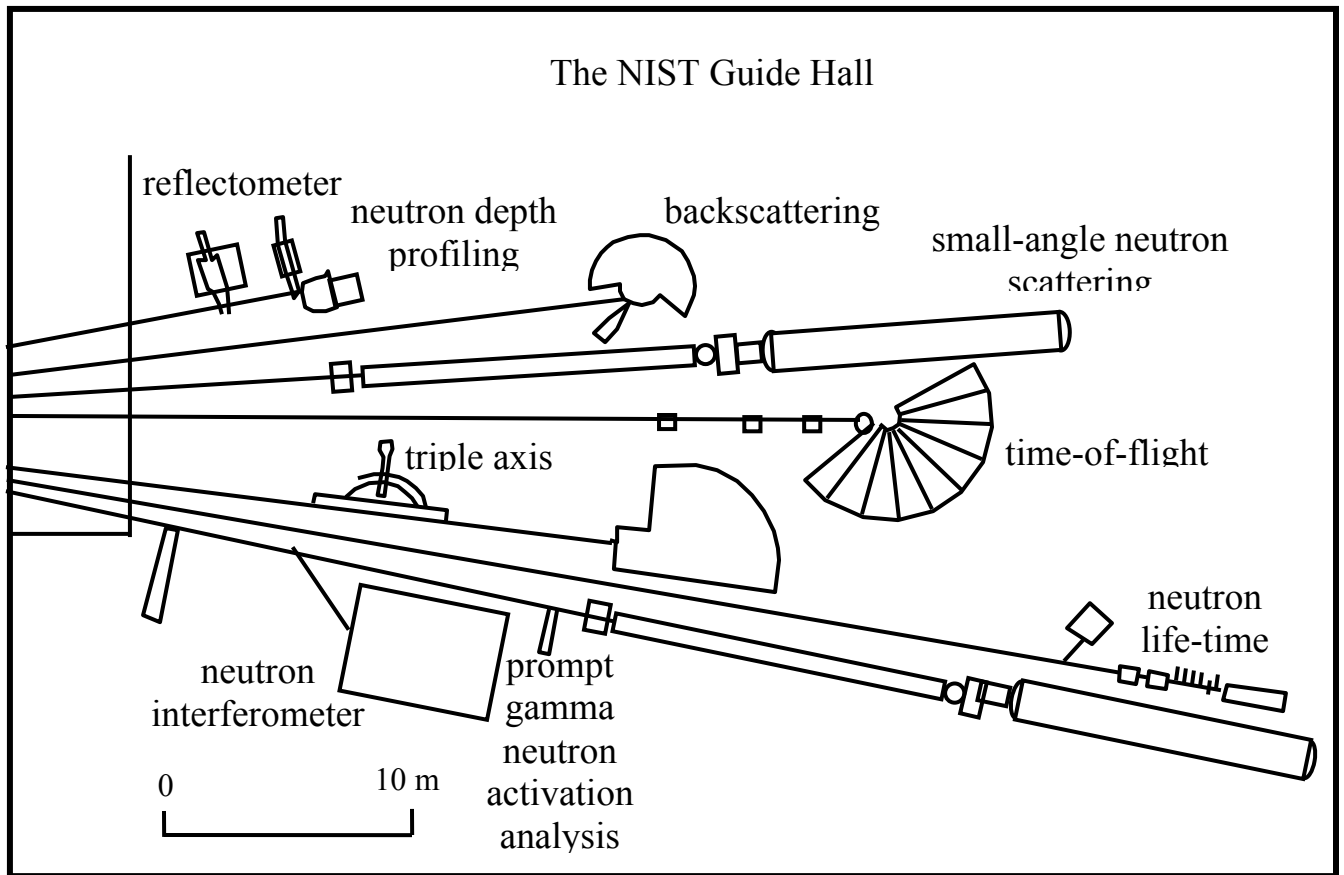


Figure 4: Schematics of the NIST CNR current guide hall.

## OTHER US NUCLEAR RESEARCH REACTORS

US nuclear research reactors fall into two main categories: research reactors have 10 MW or less power while test reactors have a higher power level. Some sixty four university-based research reactors have been built in the US (mostly in the 1960s and 1970s). Most of them are small Triga units of 1 MW or less. About twenty three are still operating [3]. The others got shut down over the years. University-based nuclear reactors are under the monitoring authority of the Nuclear Regulatory Commission. Most reactors based in national labs are part of the Department of Energy.

Table 1: List of research reactors with power of 2 MW or more.

Facility	Power
Massachusetts Institute of Technology	4.9 MW
McClellan Nuclear Radiation Center	2 MW

National Institute of Standards and Tech.	20 MW
Rhode Island Nuclear Science Center	2 MW
University of Michigan	2 MW
University of Missouri-Columbia	10 MW
Babcock & Wilcox Hanford Co.	400 MW
Idaho National Environmental and Engineering Lab.	250 MW
Oak Ridge National Lab.	85 MW
Sandia National Lab.	4 MW

## SPALLATION NEUTRON SOURCES

Hydrogen ion beams are accelerated (using a linear accelerator) to high energies (around 70 MeV) and injected into a synchrotron ring to reach much higher energies (500-800 MeV). They are then steered to hit a high Z neutron-rich target (such as W-183, Hg-200 or U-238) to produce about 10-30 neutrons/proton with kinetic energies around 1 MeV. These neutrons are then moderated, reflected, confined, etc., as done in nuclear reactor. Most spallation sources operate in a pulsed mode. The pulsed mode uses the time-of-flight method whereby “all of the neutrons (i.e., all wavelengths) are used some of the time (i.e., in pulses)”. Booster targets (enriched in U-235) help reach even higher neutron fluxes. Spallation sources are used mostly for neutron scattering.

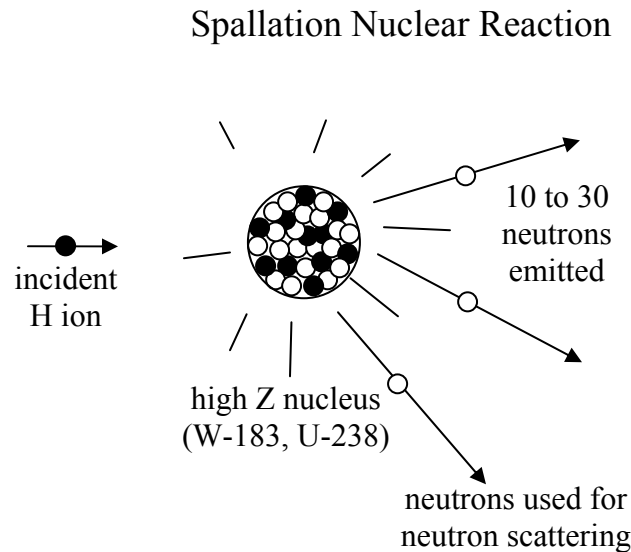


Figure 5: Spallation nuclear reaction.

Spallation sources in the USA:

-- WNR/PSR LANSCE (Los Alamos): 800 MeV protons, W target, 100  $\mu$ A (12 Hz), pulse width = 0.27  $\mu$ sec, flux =  $1.5 \times 10^{16}$  n/sec, operating since 1986.

-- SNS (Oak Ridge National Lab): 1.3 GeV, Hg target, 2 mA (60 Hz), pulse width = 0.945  $\mu$ sec, operation started in 2006.

Spallation sources elsewhere in the world:

-- ISIS (Rutherford, UK): 800 MeV protons, U target, 200  $\mu$ A (50 Hz), pulse width = 0.27  $\mu$ sec, flux =  $4 \times 10^{16}$  n/sec, operating since 1984.

-- KENS (Tsukuba, Japan): 500 MeV protons, U target, 100  $\mu$ A (12 Hz), pulse width = 0.07  $\mu$ sec, flux =  $3 \times 10^{14}$  n/sec, operating since 1980.

-- SINQ, Paul Scherrer Institut (PSI), Switzerland, 590 MeV protons, Pb target, 1.8 mA, flux =  $5 \times 10^{14}$  n/sec, operating since 2002.

The Los Alamos Spallation Neutron Source

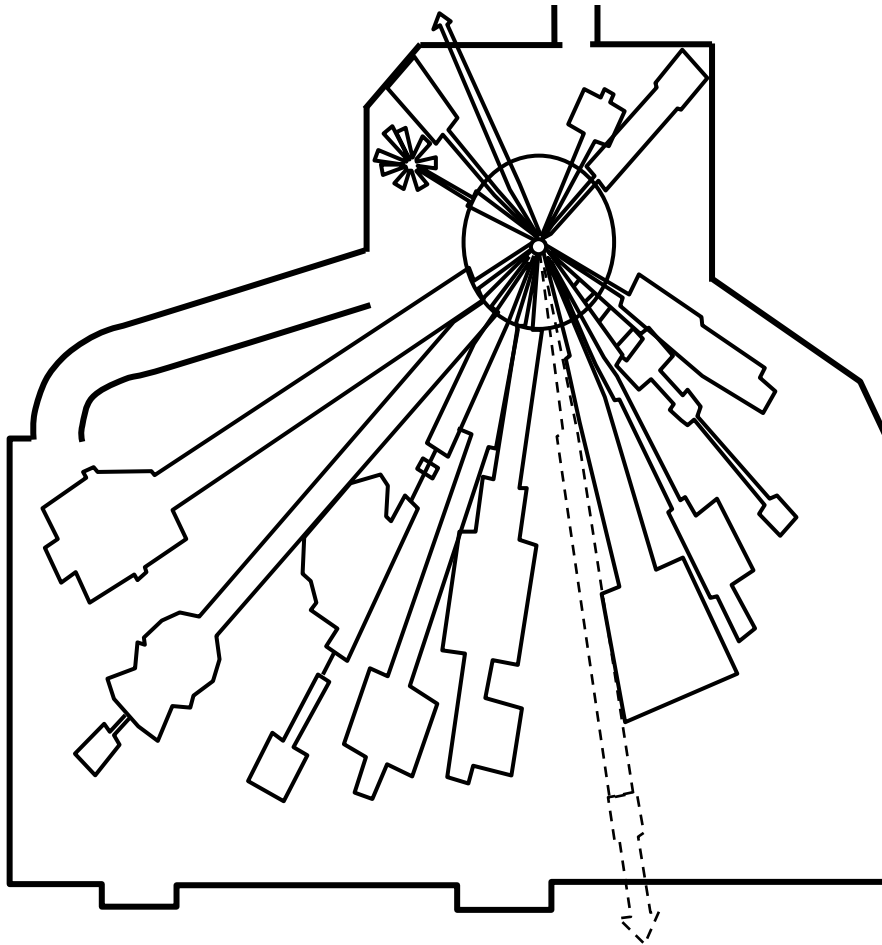


Figure 6: Schematic of the LANSCE instruments hall at the Los Alamos National Lab.

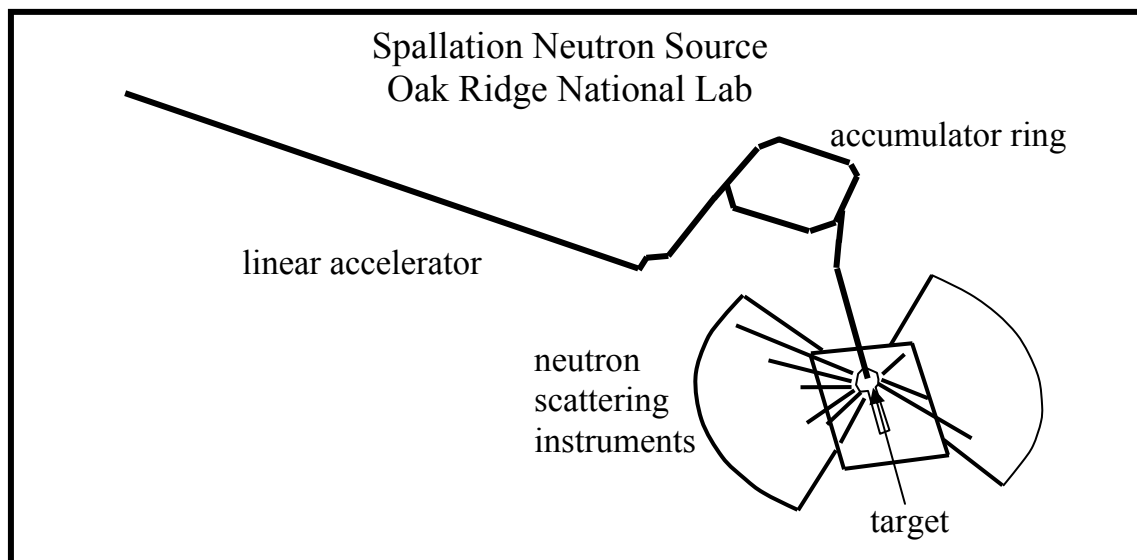


Figure 7: Schematic of the Spallation Neutron Source at Oak Ridge National Lab.

## SOME OTHER NEUTRON SOURCES

Other methods used to produce neutrons are included here. “Pulsed” reactors use a moving fuel element (or reflector material) which oscillates periodically thereby producing bursts of neutrons. One such reactor exists at: IBR-II (Dubna, Russia), with mean power of 2 MW, pulse width of 50  $\mu\text{sec}$ , repetition rate of 5 Hz.

Other low-flux neutron sources are based on the so-called (p,n) “stripping” nuclear reaction whereby a proton is absorbed and a neutron is produced. Linear proton accelerators are used to accelerate incident neutrons on the target. One such reaction uses a beryllium target and produces boron using the following reaction  $\text{Be-9}(p,n)\text{B-9}$ . This reaction is used to produce pulsed neutrons at the Low Energy Neutron Source of the University of Indiana with pulse width between 5  $\mu\text{sec}$  and 1 msec. Compact linear accelerators are sometime used to make portable neutron sources that can be used for field measurements.

Other portable neutron sources use alpha emitters such as americium surrounded by a neutron rich blanket such as beryllium. The AmBe source uses the  $(\alpha,n)$  reaction to produce “neutrons in a bucket”. Alpha particles are He-4 nuclei.

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## NEUTRON ACTIVATION ANALYSIS

### THE NEUTRON ACTIVATION ANALYSIS TECHNIQUE

The Neutron Activation Analysis (NAA) method consists in irradiating samples in a neutron source then measuring the gamma radioactive decay. Specific gamma peak energies point to what elements are in the sample and the area underneath the peaks points to the relative amount of each element. NAA can detect trace elements with high accuracy. Most elements that are heavier than oxygen can be detected at the parts per million (ppm) level or lower. It is more accurate and more sensitive than other analytical characterization methods that monitor atomic transitions. NAA benefits from the high fluxes found in nuclear reactors.

NAA sample irradiation is performed in the reactor core or in the reflector region. Pneumatic or hydraulic tubes are used to deliver small samples encapsulated inside plastic tubes (called rabbits) to the irradiation area and back. Irradiated samples end up in measurements labs for gamma counting [1,2]. In order to quantify absolute amounts of each element in the sample, precise estimate of the neutron flux (number of neutrons/cm<sup>2</sup>.s) at the irradiation spot must be known. This is most-often performed by irradiating a gold foil sample for which the absorption cross section is well known. Time zero corresponding to the end of the irradiation process and to the beginning of the radioactive decay must be recorded precisely. The number of activated nuclei in the sample decays exponentially as  $N(t) = N_0 \exp(-t/\tau)$  where  $\tau$  is the decay lifetime. The half-life is the time that it takes for half the nuclei to decay and is related to  $\tau$  as  $t_{1/2} = \tau \ln(2)$ .

Gamma spectroscopy measures gamma ray spectra consisting in the number of emitted photons with varying photon energy. Wide energy windows can be measured using multichannel analyzers. Gamma detectors use scintillation crystals (NaI), semiconductor materials (SiLi) or high purity germanium (Ge) as detection materials.

Compact portable gamma sources are used to calibrate the detectors response. These include Ba-133 which emits gamma rays with energies of 81 keV and 356 keV, Cs-137 with a characteristic photopeak at 661.64 keV and Co-60 with two characteristic photopeaks at 1173.23 keV and 1332.51 keV.

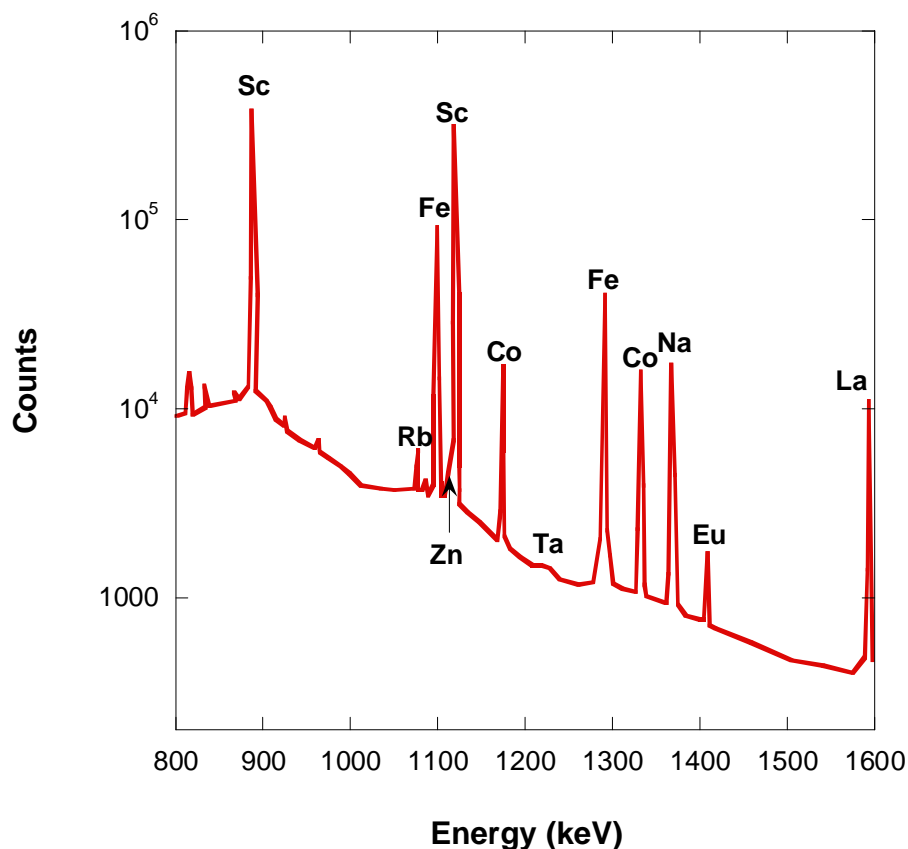


Figure 1: NAA spectrum showing the photopeaks of many elements.

Sometime irradiated samples are treated through chemical separation in order to concentrate the radioisotopes of interest. Radiochemistry is performed in specially regulated laboratories.

### A FEW APPROXIMATE DETECTION LIMITS

NAA detection limits depend on what element is being measured. A few detection limits are included here. Manganese, indium and europium can be detected at the  $10^{-12}$ - $10^{-11}$  g levels. Chlorine, titanium, zinc, platinum, mercury and thorium can be detected at the  $10^{-9}$ - $10^{-8}$  g levels. Silicon, sulfur and iron can be detected at the  $10^{-6}$ - $10^{-5}$  g levels. These limit estimates are for an irradiation flux of  $1 \times 10^{14}$  neutrons/cm<sup>2</sup>s, a 1-hour irradiation time and a 1-hour counting time. Decay half-lives for the various elements vary from a few seconds (oxygen, fluorine, etc.) to years (zinc, gold, etc.). When the half-lives are too short for the conventional NAA technique to be used, activation and prompt gamma detection are performed simultaneously. This technique is called the Prompt Gamma Neutron Activation Analysis (PGNAA) which is used for elements such as: hydrogen, boron, carbon, nitrogen, silicon, sulfur, cadmium, gadolinium and mercury.

## **BIOMEDICAL STUDIES**

NAA is used to quantify the presence of many elements in harvested tissue or body fluids. It helps figure out their role in metabolic functions. One sample preparation method consists in drying and cutting the specimen before neutron irradiation. A few examples follow [3].

Calcium is the major element in bone formation. Calcium deficiency leads to bone disease; bones become brittle making them prone to fracture. Assessing calcium levels in the body has provided data for the diagnosis and understanding of a number of metabolic bone disorders including osteoporosis. Loss of calcium has also been linked to chronic kidney malfunction.

Iodine is used by the thyroid gland to produce hormones that affect the growth of many systems in the body. Iodine deficiency results in an enlarged thyroid gland (goitre). It can also affect the growth of children in many poor countries. Iodine is routinely added to table salt to ensure proper iodine intake levels.

A series of nutritional studies have concentrated on assessing the role of selenium intake and its relation to the occurrence of some diseases. Selenium deficiency has been observed in very old people (over 90) and in patients that have undergone gastrointestinal surgery. Selenium deficiency can lead to the weakening of the heart. It can also lead to increased susceptibility to infectious diseases. Various governments have set minimal selenium intake regulations (between 55 and 75  $\mu\text{g/day}$ ).

Hypertension (commonly called high blood pressure) affects many people. It is one of the risk factors for stroke or heart attack and is a leading cause of kidney failure. High cadmium levels in the kidney and liver have been related to hypertension.

Alzheimer's disease (also called old age dementia) affects brain function and diminishes the quality of life through increasing impairment. It places great burden upon health givers that have to attend to every need of the affected patient for long term. The presence of aluminum in the brain has been linked to the Alzheimer disease.

## **ENVIRONMENTAL MONITORING**

Slow changes in the environment and their impact on living species are oftentimes hard to assess. Specimen banking is one way of gathering valuable information that may help detect changes and find causes for such changes. Oysters from the Chesapeake Bay (on the eastern Maryland shore) have been conserved over many years in order to assess the effect of runoffs on this marine species along the coast. The NAA technique is valuable in detecting trace elements of various contaminants. The levels of polychlorinated biphenyls (also called PCBs) for instance are closely monitored. Moreover, fumes from car exhaust end up covering up roads and parking lots. These are washed by rain water

down streams and rivers till they reach the bay. Such carbon-based pollution is a serious problem.

NAA has been used to monitor contaminants in order to assess levels of environmental or occupational exposure to toxic substances that are airborne or in the water cycle. A study was focused on detecting trace amounts of mercury in the hair of fishermen in Japan in the early 1970s. Abnormal levels of mercury in fish lead to kidney and neurological disorders. Another case involved “cracking a detective story” using clues from NAA. During the 1970s there was a food poisoning crisis in Spain whereby some 300 people died. Poisoning was traced to the presence of chlorine in olive oil. NAA helped figure out that large amounts of cheap (toxic) seed oil were added to the expensive olive oil in order to increase profits. In another instance (during the 1980s) many people died in the United States after taking Tylenol capsules. NAA helped detect trace amounts of arsenic in some remaining capsules that were traced back to a batch that was tempered with.

NAA is highly sensitive to rare earth metals (such as indium, lutetium, lanthanum, etc) which are emitted by industrial plants. Monitoring of such industrial pollution is performed routinely. Car exhaust contains toxic particulates (along with carbon monoxide and sulfur dioxide) from burnt gasoline in combustion engines. Catalytic converters are used to remove such toxic substances from exhaust pipes by using catalysts such as palladium and platinum. Trace amounts of these metals have been found in lung tissue of people living in cities with high levels of exhaust pollution. This is not a serious problem, but continued monitoring is warranted.

Boron levels in the atmosphere and in soils are also monitored. Boron is an essential plant nutrient. Most plants have a narrow window between boron deficiency and toxicity levels. Plants use boron to maintain the integrity of plant cell walls. Boron imbalance can have detrimental effect on plant growth thereby affected the food supply.

Prompt gamma activation analysis is used routinely for real time monitoring of specific elements in the industrial processing of ores under bulk handling conditions. For example the sulfur and moisture content of coal are monitored in coal plants.

## **TRACER STUDIES**

The NAA technique is also useful when used with tracers (stable elements) that are entered into natural biocycles and neutron activated later in order to determine their pathways and metabolic distribution. For example, pine trees containing excess manganese have been used to monitor the propagation of pollen in the environment.

Gold is omnipresent in metabolic processes. It is also present in many pharmaceutical products. Assessing the beneficial and harmful effects of gold in the body is important. A gold tracer study is described here [4]. Gold nanoparticles that are attached to polypeptides (called affibodies) were injected into laboratory mice known to carry tumors. Tissues from the various organs (kidney, liver, blood, spleen, lung, intestine,

heart, pancreas, bone and muscle) as well as from tumor tissue were then harvested at various times after injection, freeze dried, then irradiated for NAA analysis. Upon neutron absorption, a number of reactions take place (as depicted below). Beta decay of Au-198 into metastable nuclide Hg-198\* is followed by gamma ray emission (at 411.8 keV). The amount of gold in each of these tissues was quantified. Some of the conclusions of this study were that liver and kidney tissue accumulated the most amount of gold. Gold concentration peaked at 8 hours after injection in most tissues. Moreover, there was evidence that gold accumulated in tumor tissue.

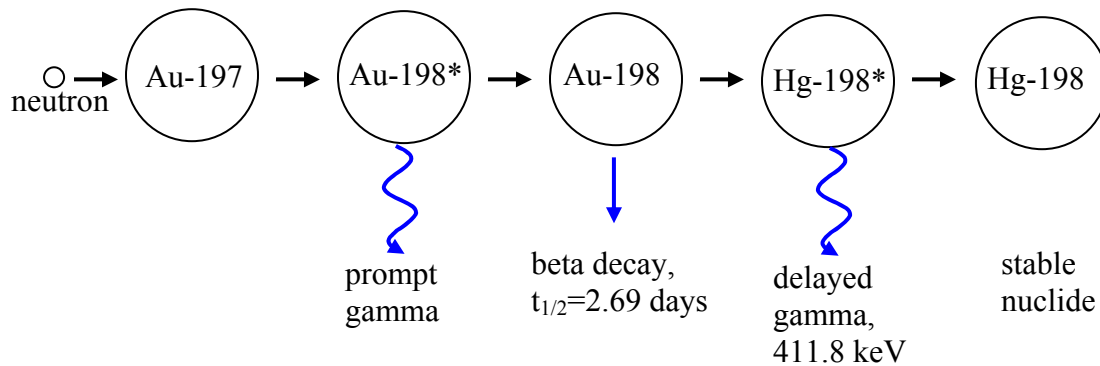


Figure 2: Thermal neutron absorption produces a series of reactions involving gold (Au) and mercury (Hg).

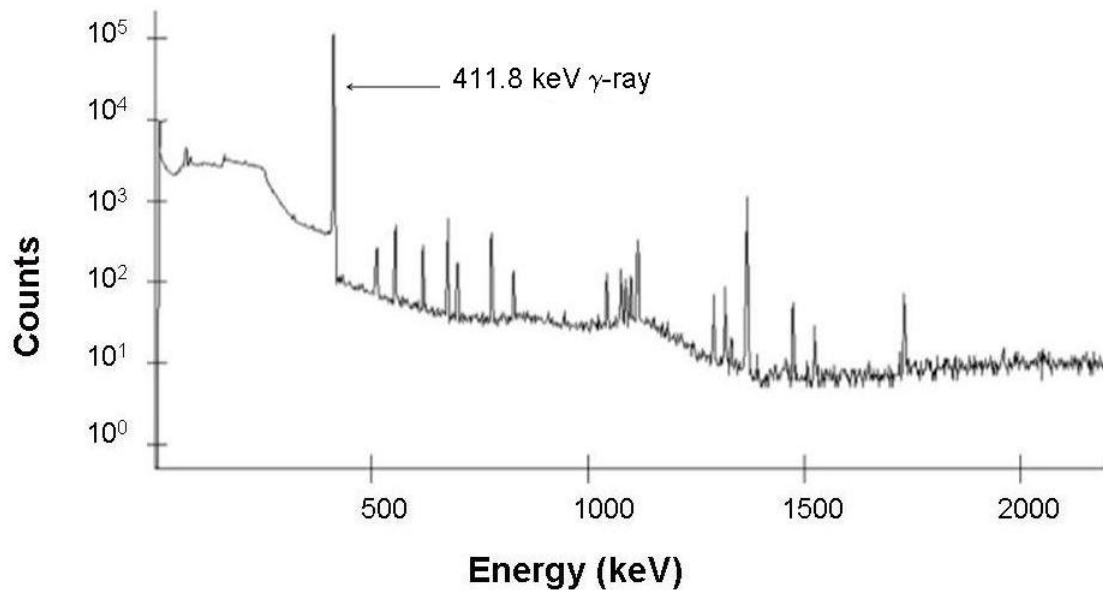


Figure 3: The 411.8 keV gamma ray line following the decay of Hg-198\* is clearly visible.

Note that the (411.8 keV) gamma ray is emitted by Hg-198 but is a signature of the presence of the parent isotope Au-198 which is produced by neutron capture of stable gold (Au-197). That gamma ray line is therefore evidence of the presence of gold.

## GEOLOGICAL APPLICATIONS

NAA is used to conduct geological surveys, to document the sedimentation distribution of various elements and for oil and mineral exploration. It helps in the analysis of minerals in order to gauge their worth as ores. It has been applied to rocks from earth, from the moon as well as from meteorites. For example, NAA was used to analyze a meteorite collected in Australia in 1969. This is referred to as the Murchinson meteorite. Some nucleotide bases (for example uracil) that make up DNA and RNA were identified in that meteorite. DNA is the essential genetic material found in chromosomes. It codes for the synthesis of proteins and is the basic blueprint for life. In order to verify that this was not due to contamination from Earth, the C-12/C-13 ratio was measured and found to be around 42. This number is characteristic of meteorite content; on Earth, that ratio is close to 90. This finding increases the odds of finding life elsewhere in the universe and adds a clue that life on earth may have come from elsewhere.

A thin iridium-rich layer was uncovered in many places around the world [5]. This 1 cm-thick layer was exposed at a depth of 256 meters and was correlated with depletion in pollen count at the same depth. This suggests a massive sudden loss of plant life on earth some 65 million years ago. Since iridium is found in meteorites, it was concluded that the impact of a huge meteorite (asteroid) on earth may be the cause of this global disaster. This event was linked to the extinction of the dinosaurs which happened at around the same time in earth history. This discovery was made by the Nobel Prize winner in Physics Luis Alvarez.

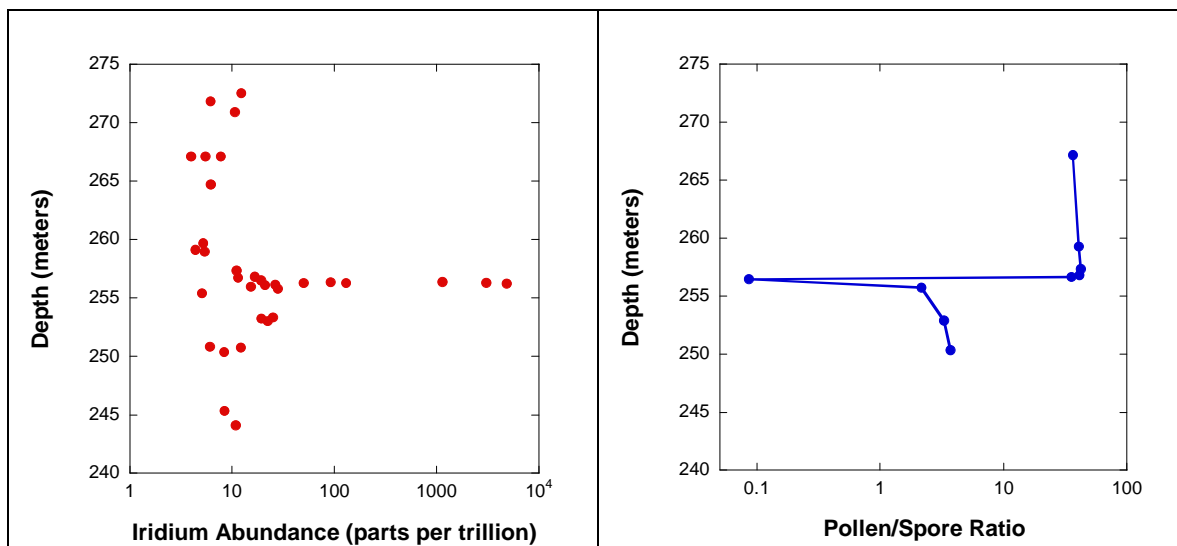


Figure 4: A thin layer of iridium was detected by NAA. This layer was related to the extinction of the dinosaurs some 65 million years ago.

## **VOLCANO ERUPTIONS**

NAA was used to measure trace amounts of gold in tree rings and link this finding to volcanic eruptions [6]. The technique consists in cutting wood sections from the various tree rings of a very old tree and measuring the trace amounts of gold in each ring. Tree rings that held the highest amount of gold were related to documented events of known volcanic eruptions. Correlations were found with known volcanic eruptions over the past 500 years. The technique can be used for longer periods of time extending to thousands of years depending on the availability of trees that are that old.



Figure 5: Trace amounts of gold are detected in tree rings and related to volcanic eruptions.

## **ARCHEOLOGICAL APPLICATIONS**

The NAA technique has been effective at identifying the source and time origin of various artifacts from previous civilizations. This helps reconstruct aspects of past history such as trade routes, outside invasions, far-reaching influences, etc [3]. For example, sharp obsidian glass was used to manufacture cutting tools, arrow tips and decorative objects in prehistoric Mesoamerica. Such objects found throughout Central America were traced back to a volcanic origin in Mexico.

NAA has also been used to trace the provenance of pottery objects back to their manufacturing source. Pottery found far from its origin is a sign of far-reaching trade. A sudden alteration in pottery style is a sign of foreign invasion. The analysis of Greek

objects (such as vases) helped catalog the period of their origin. Correlation clusters were identified for objects of similar origin.

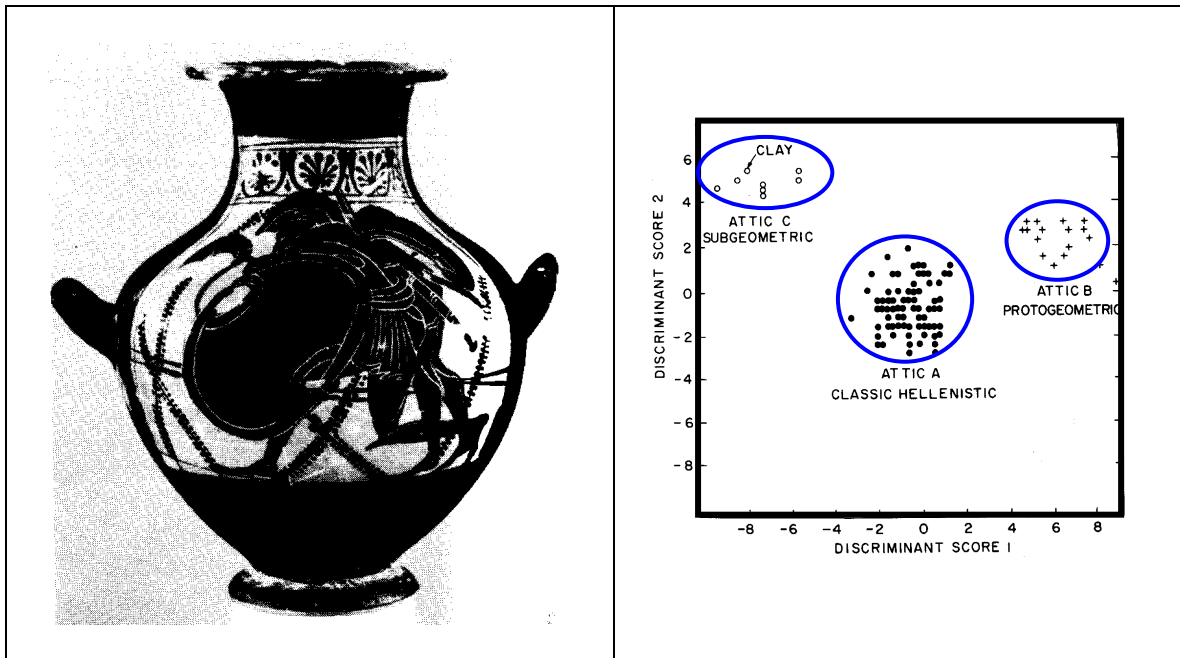


Figure 6: NAA is used to determine the provenance of art objects. A Greek vase is shown on the left and statistical clusters corresponding to different pottery periods are mapped out on the right.

Mesoamerican jades manufactured between 600 AD and 900 AD were traced back to the Motagua River valley in Mayan territory (present day Guatemala). In another case, medieval limestone reliefs found in many parts of France were traced back to the Perigord region in the south.

## FORENSIC SCIENCE

Law enforcement agencies have many analytical tools at their disposal for evidence gathering. Elemental analysis involves chemical and spectroscopic characterization of objects (such as soil, fibers, body fluids, etc) in order to link a suspect to a crime. NAA has been an accepted evidence-gathering tool in the United States since 1959. For example, trace amounts of gunshot powder can be detected on the hand of someone who has fired a gun for up to 2 days after the firing and even if the firing hand has been washed extensively with soap. Taking a swab or wax imprint of the hand is followed by conventional chemical analysis which can detect the major components of gunpowder or explosives. These methods are quick (under 10 minutes) and readily available. NAA is usually performed when such methods do not yield results or when higher accuracy is required.



Figure 7: NAA is used to detect trace elements of gun powder.

## ART HISTORY

NAA has also been used as a non-destructive analysis tool to authenticate art pieces such as paintings [7]. X-ray films are placed in contact with the painting after neutron irradiation to obtain autoradiograph pictures at different decay times. Such images can unravel valuable information such as hidden brush strokes or underneath painting layers. Different paints contain different chemical compositions (pigments) and get activated differently under neutron irradiation. In one instance, the autoportrait of the famous Flemish artist Van Dyck was discovered underneath his masterpiece "Saint Rosalie Interceding for the Plague-stricken of Palermo" [8]. The artist had apparently decided to reuse the canvas and repainted over his self-portrait. This turned out to be the only known self-portrait of this artist.



Figure 8: “Saint Rosalie Interceding for the Plague-Stricken of Palermo” painted by the Flemish painter Anthony van Dyck in 1624 on the left. Autoradiography unraveled the self portrait of the painter underneath shown on the right.

In another instance, neutron autoradiography uncovered hidden details under a painting by the American painter Thomas Wilmer Dewing. When he adopted the surrealist style, he removed (painted over) the pieces of furniture on his famous nude painting making the woman seem to float in the air.

## **HYDROGEN STORAGE MATERIALS**

The limited supply of oil in the world has led to efforts to find alternative fuel sources. Hydrogen is one of these alternative fuels. Hydrogen storage technology is a major component in that effort. Single wall carbon nanotubes (SWNT) are candidate materials for hydrogen storage. These form nanoscale carbon structures that can bind hydrogen. Substituting boron for carbon increases the binding efficacy of hydrogen. The nuclear reaction  $B-11(n,\alpha)Li-8$  produces radioactive lithium (Li-8) which decays with a very short half-life (less than a second). For this reason, the prompt gamma neutron activation analysis (PGNAA) is used instead. The PGNAA technique [9] was used to quantify the amount of boron atoms as well as the level of cobalt and nickel catalyst in these materials. Boron shows up as an impurity material. Boron is also used as dopant to enhance storage ability. The addition of this dopant was seen to enhance the overall background level and is characterized by a well-defined photopeak at 475 keV. Note that

the photopeaks for hydrogen (2223 keV) and carbon (4945 keV) are outside of the plotted gamma energies window.

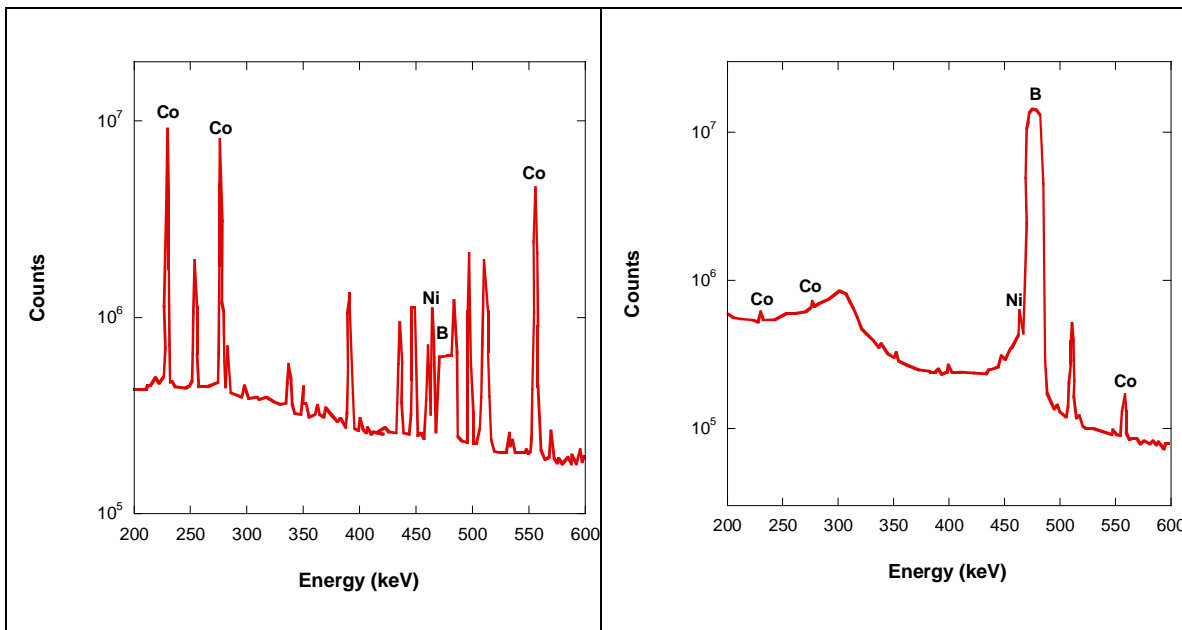


Figure 9: PGNA from carbon nanotubes on the left and from boron-doped carbon nanotubes where some carbon was substituted with boron on the right.

## LAST WORD ABOUT NAA

The NAA method is a very sensitive technique that can unravel clues not detected by other chemical methods. NAA's limited availability makes it an extravagant option. Its unusual sensitivity (lower than parts per billion) makes it unique within the panoply. NAA, however, is a nuclear method and therefore cannot yield direct information about atomic binding or molecular compositions; it can only yield atomic compositions. Moreover, it is sensitive to some atoms more than to others.

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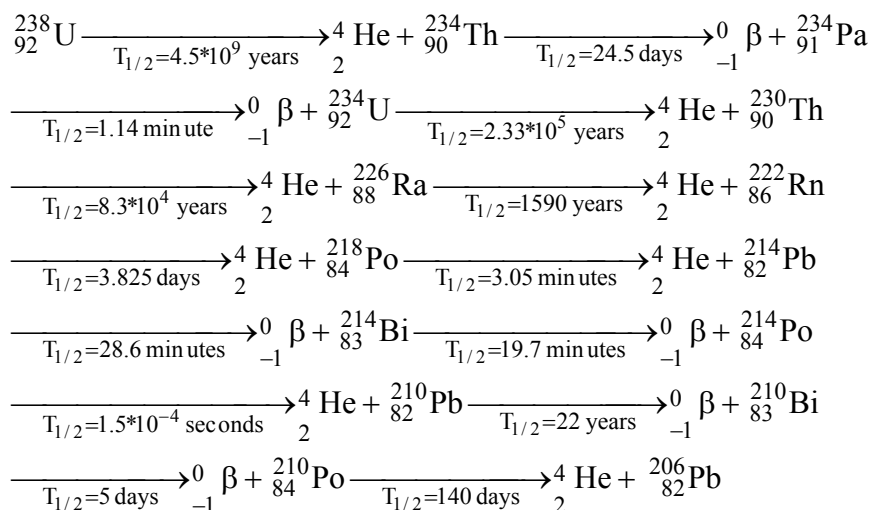
## RADIOISOTOPES APPLICATIONS

There are some 300 stable isotopes and 1300 known radioisotopes. Most radioactive elements are produced through neutron irradiation (in reactors) or charged particle bombardment (using particle accelerators). Radioactive isotopes decay by emitting charged particles (alpha, beta, positrons) and/or gamma rays [1,2,3]. The production rate of radioisotopes depends on the capture cross section of the parent element, on the irradiation flux and on the decay half-life of the produced radioisotope. Most reactor produced radioisotopes are beta and gamma emitters. Most positron emitters are produced using particle accelerators. Natural and artificial (man-made) radioisotopes have been used in a wide variety of applications.

### NATURAL RADIOISOTOPES

Naturally occurring radioactive elements include Th-232, U-233, U-235, K-40, V-50, Rb-87, Cd-113 and In-115. A couple of these natural radioisotopes are considered in what follows.

It is not unusual to find earthenware items (such as plates, mugs or clay pots) that contain natural radioisotopes in the shiny glaze finish which contains small amounts of uranium. For example, fiesta red glaze was obtained by adding uranium oxide in the glaze. This line of products was manufactured from the 1930s to the 1970s in the US. Some can still be found in second hand stores. The major uranium isotope (U-238) is at the top of a long radioactive decay chain leading to many beta and alpha emitters and ultimately to stable lead (Pb).



Note that alpha particles ( ${}_2^4\text{He}$  nuclei) are stopped by a sheet of paper while beta particles (electrons) are stopped by an aluminum plate. Studies have shown that minor exposures resulted in using such earthenware. The practice of using uranium oxide for the

glaze was stopped in the US in the 1970s but continued in other (poorer) parts of the world.

A salt substitute (KCl) sold in grocery supermarkets contains measurable amounts of naturally occurring K-40 radioisotope which has a natural abundance of 1.17 % and a very long half-life of 1.25 billion years. K-40 decays by emitting a beta particle, a positron and by electron capture. The decay scheme for beta emission is

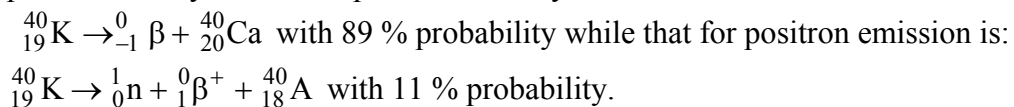


Figure 1: A Geiger counter is used to detect radioactive decay from uranium containing glaze on a ceramic plate on the left. The needle is reading 25,000 counts per minute (cpm). On the right, some salt substitute containing K-40 was poured into a petri dish. The Geiger needle shows radioactive decay and is reading 200 cpm.

The second reaction whereby potassium decays into argon is used for the dating of rocks. If the rock-producing magma contains K-40, then upon cooling, this isotope starts producing K-40 which gets trapped in the solidified rock.

There is a multitude of radioactive consumer products such as bathroom tiles, welding rods, thorium containing camera lenses, Brazil nuts, some spark plugs, some fertilizers, radioactive watch fluorescent handles, etc [4]. When these products are found to be radioactive, they are usually pulled out of the market if their effect is deemed to be harmful.

## RADIODATING

Carbon has three isotopes, two of which (C-12 and C-13) are stable and the third one (C-14) is radioactive. A form of carbon radiodating uses the ratio of C-12 to C-14 to date organic matter on a scale of 10,000 years. The naturally occurring isotope C-14 is produced through the reaction  $\text{N-14}(n,p)\text{C-14}$  in the atmosphere by capturing neutrons

that are produced by cosmic radiation. C-14 (in carbon dioxide for example) gets trapped in a form which ceases to exchange with C-12 and is therefore a time clock marking the trapping time. Carbon dioxide (in the C-14 and C-12 forms) is absorbed by plants that leave organic matter behind. Animals that eat these plants will also contain C-14 in their tissues and bones. C-14 decays through beta emission. Assessing the relative amount of C-14 with respect to the stable C-12 allows an estimate of the time when a plant or animal was living. The long half-life (5,730 years) of C-14 permits dating over a long time scale. This method is calibrated using an old piece of organic matter of well known age; for example, a piece of wood that belonged to a specific pharaoh. The Nobel Prize in Chemistry was awarded to Willard Lilly in 1960 for developing this carbon-14 method of age determination.

Other radiometric dating methods on a much longer time scale are used. The U-234/Th-230 ratio in rocks and other geological formations dates in the 100,000 years time range. U-234 decays to Th-230 by emitting an alpha particle with a half-life of 233,000 years. Measuring the relative amount of U-234 allows an estimate of the age of rocks (elapsed time since they solidified). Another dating method uses the Rb-87 to Sr-87 beta decay which has a half-life of order 50 billion years. This method is used to date igneous and metamorphic rocks and has been used to date lunar rocks. Note that the age of the universe (14 billion years) is shorter than this half-life.

## **MEDICAL RADIOISOTOPES**

Radioisotopes are used in one of the following ways in medicine [5]. Gamma ray emitters are used as tracers for the diagnostics of organ function. They are used to image various internal organs. Beta emitters (mostly) are used as high dose carriers for specific radiation therapy treatments. So many radioisotopes have been developed over the years that they can be tailored to specific applications depending on the form and half-life of the emitted radiation and on the energy deposited. Most radioisotopes are gamma and beta (or positron) emitters but there are a few alpha emitters (such as At-211 or Bi-212). Alpha emitters deliver doses that are very high to a very small spot.

A well-known molybdenum (or Moly for short) isotope Mo-99 which is a beta emitter gets attached to monoclonal antibodies. These are clones of specific organ cells that tend to seek and bind to the same type of cells. Monoclonal antibodies are a means to deliver specific radioisotopes to cancerous cells. Mo-99 emits betas as well as 1.2 MeV gamma rays with a half-life of 67 hours.

Another radioisotope known as a radiotracer is Tc-99m which emits 140 keV gamma rays with a half-life of 6 hours. This convenient half-life is long enough for diagnostic procedures to be conducted but keeps radiation exposure to the patient low. Tc-99m decays to Tc-99 (by emitting gamma rays) which decays to Ru-99 by emitting beta particles with a half-life of 211,000 years but no gamma rays. This decay scheme helps keep the radiation burden to the patient to a minimum. Due to its short half-life, Tc-99m is not obtained by irradiation in a nuclear reactor; it is instead obtained using a

radioisotope generator through the radioactive decay of Mo-99 mentioned before (half-life of 67 hours). This parent radioisotope Mo-99 is continuously decaying thereby producing the short half-life radioisotope Tc-99m (half-life of 6 hours). This daughter product is flushed down into a vial just prior to injection. Radioisotope generators are referred to as “cows” that can be “milked” on site. The Mo-99/Tc-99m generator is used for brain imaging (among others) and for diagnostic purposes to evaluate brain function.



Figure 1: A radioisotope generator uses the continuous decay of a long half-life parent to produce a short half-life product.

The earth metal element strontium has many isotopes, one of which (Sr-89) is used for radiation therapy of metastatic bone cancer. When injected, it tends to concentrate in bones and delivers its beta dose with a half-life of 50.5 days. Note that strontium tends to accumulate in bones because the outer electronic shell structure of that atom is similar to that of calcium (both are on the second row of the periodic table). Sr-89 is also a gamma emitter; these gamma rays are used to image diseased bones. Other radioisotopes such as Sm-153 and I-131 are also used for the radiation therapy treatment of metastatic bone cancer. The Re-186 bone-seeking agent is used to relieve the intractable pain associated with the metastasis of bones following breast, lung or prostate cancers. It can also reduce the size of such tumors.

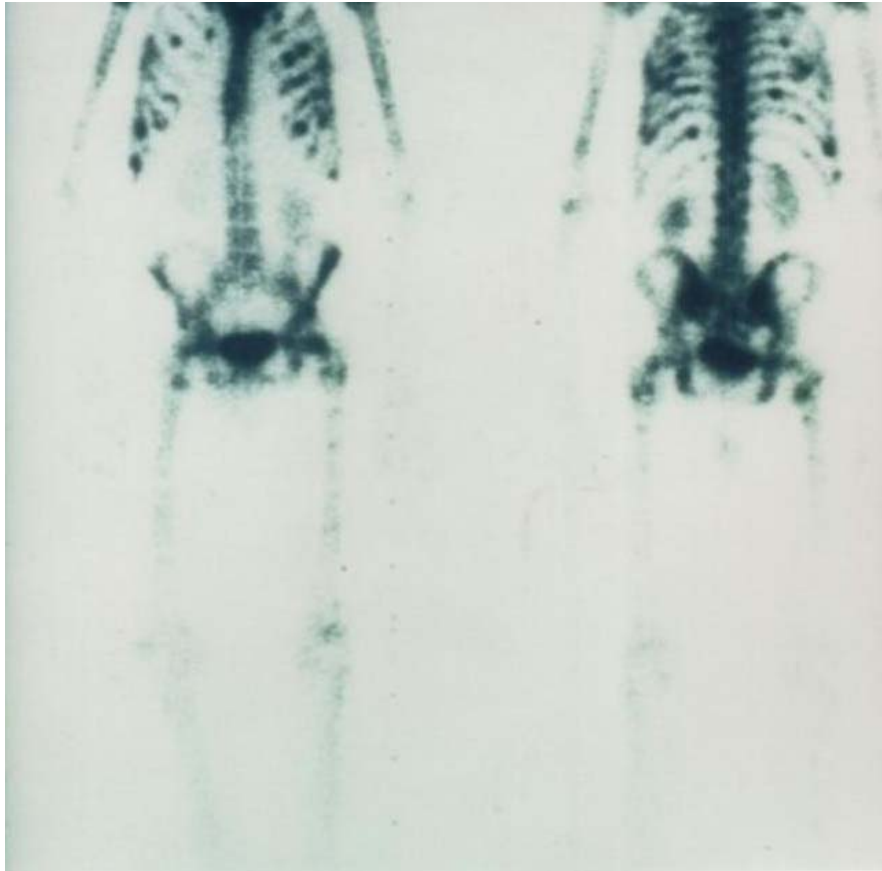


Figure 2: Sr-89 is used to treat metastatic bone cancer. This whole body radiograph shows generalized bone cancer in a patient.

The decay of I-131 to Xe-131 emits beta particles and gamma rays with a half-life of 8 days. Gamma energies are 364 keV and 606 keV. I-131 is a fission product obtained through the fission of U-235. I-131 is used in nuclear medicine both for diagnostics and for therapy. It is used for example for the radiation therapy of thyroid cancer (by injection treatment). Thyroid nodules are found around the neck region during routine physical examination of patients. This diagnosis is often followed by ultrasound imaging and other diagnostics methods to confirm the medical condition. Chemotherapy and radiation therapy are the best course for curing such cancers. Thyroid cancer may require surgery as well.

After injection of a radioisotope into the human body or into a specific organ, imaging of the emitted gamma rays is performed using an Anger scintillation camera. This camera detects gamma rays with high resolution thereby producing clear images of internal organs when x-ray imaging is not sensitive enough. Anger cameras are used to image gammas from many radioisotopes. For example, the Ir-192 radioisotope is used with Anger cameras. Sometimes the injected radioisotope delivers a beta dose to tumors as well as emits gammas for imaging purposes.

In cases where the patient could not be transported to an x-ray imaging facility (such as in the surgery room for example), compact gamma ray cameras are used on site. These use radioisotopes that emit gamma rays with appropriately long half-lives. One of these gamma ray cameras is called the Lexiscopes and uses I-125. Its half-life is 59 days and emits “soft” (35 keV) gamma-rays suitable for imaging.

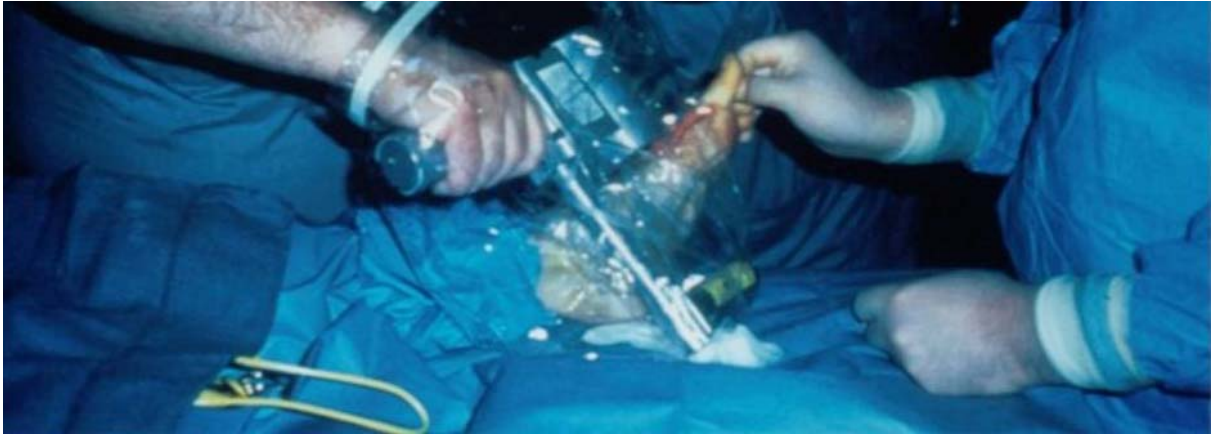


Figure 3: The Lexiscopes is a portable gamma ray camera.

The Y-90 radioisotope is injected into the bloodstream to treat neoplasm (abnormal growth of tissue). It decays by beta emission (half-life of 2.67 days) and is used for the radiation therapy of metastatic liver cancer. Y-90 glass microspheres are injected into the aorta artery which leads them through the lungs to the liver. Their characteristic size (20 to 30 microns in diameter) gets them trapped in the liver where they deliver a localized dose. P-32 labeled glass microspheres are also used to treat liver cancer. It has a longer half-life (14 days) thereby delivering its beta dose over a longer period of time. P-32 also emits gamma rays and is used to image the liver using the Anger scintillation camera during the treatment.

Pd-103 seeds are used for radiation therapy of prostate cancer. These seeds are implanted at the base of the prostate using long needles. They deliver soft gamma rays (energy of 21 keV) within a reasonable period of time (17 days half-life). Since each seed treats a localized area, many (up to 100) seeds are placed to cover the entire prostate gland. The radiation exposure of other organs is minimized. An ultrasound probe is introduced into the rectum to image the prostate area. This on-screen imaging technique helps guide the needle used to implant the seeds.

Re-188 labeled monoclonal antibodies are used for targeted therapy of acute leukemia. These are cells that mimic white blood cells and end up concentrating in the bone marrow. This therapy delivers an effective and localized dose to where it's needed. The half-life of Re-188 is 17 hours.

It should be noted that radioisotopes used for medical studies and for various cures have documented harmful effects because they destroy healthy cells along with the cancerous ones. Radioisotope treatments are prescribed when other treatments are ineffective.

Table 1: Summary of some radioisotopes used in nuclear medicine

$^{99}_{42}\text{Mo} \rightarrow ^{99\text{m}}_{43}\text{Tc}$ $T_{1/2}=67$ hours	Parent element in radioisotope generator
$^{99\text{m}}_{43}\text{Tc} \rightarrow ^{99}_{43}\text{Tc}$ $T_{1/2}=6$ hours	Brain, liver, spleen and kidney imaging
$^{89}_{38}\text{Sr} \rightarrow ^{89}_{39}\text{Y}$ $T_{1/2}=50.5$ days	Radiation therapy of bone cancer
$^{153}_{62}\text{Sm} \rightarrow ^{153}_{63}\text{Eu}$ $T_{1/2}=46$ hours	Radiation therapy of bone cancer
$^{131}_{53}\text{I} \rightarrow ^{131}_{54}\text{Xe}$ $T_{1/2}=8$ days	Radiation therapy of bone cancer and thyroid cancer
$^{192}_{77}\text{Ir} \rightarrow ^{192}_{78}\text{Pt}$ $T_{1/2}=74$ days	Used in the Anger camera
$^{125}_{53}\text{I} \rightarrow ^{125}_{54}\text{Te}$ $T_{1/2}=59$ days	Used in the Lexiscope camera
$^{90}_{39}\text{Y} \rightarrow ^{90}_{40}\text{Zr}$ $T_{1/2}=64$ hours	Radiation therapy of liver cancer
$^{32}_{15}\text{P} \rightarrow ^{32}_{16}\text{S}$ $T_{1/2}=14$ days	Radiation therapy of liver cancer, image the liver using the Anger camera
$^{103}_{46}\text{Pd} \rightarrow ^{103}_{47}\text{Rh}$ $T_{1/2}=17$ days	Radiation therapy of prostate cancer
$^{188}_{75}\text{Re} \rightarrow ^{188}_{76}\text{Os}$ $T_{1/2}=17$ hours	Radiation therapy of acute leukemia

## RADIOTRACER MEDICAL STUDIES

Many radioisotopes are used as tracers in medical studies to investigate physiological function and transport pathways in living biological systems. Foods containing mild radioisotope amounts are ingested by human subjects in scientific studies in order to investigate metabolic processes and food processing schemes by the body. Gamma activity is monitored in the blood, feces and urine. For example, radioactive iron-enriched cereals and calcium-enriched milk were given for breakfast to young people in a Harvard/MIT study. In another study, the absorption of zinc (use of Zn-65 radiotracer) was investigated in a vegetarian diet and compared to meat diets with equal concentration of phytic acid (phytic acid is the principal storage form of phosphorus in many plant tissues). The vegetarian diet resulted in a lower amount of absorbed zinc since high zinc levels are contained in meats [6].

Radioisotopes can also help monitor the response to a treatment. Tracers such as H-3, P-32, Cr-51, Fe-55 and I-125 are used in conjunction with autoradiography to study cell function in laboratory animals. In one study, the efficacy of various chemotherapeutic agents on leukemia cells was assessed. In another, the Pt-195m radiotracer was used to monitor chemotherapeutic uptakes administered for brain tumor treatment.

## INDUSTRIAL APPLICATIONS

Radioisotopes have also found uses as tracers and for onsite imaging in industrial processes. Ir-194 is used for onsite radiography to detect machine wear, locate cracks or leaks, to examine welds in metals and for various forms of online diagnostics [7].



Figure 4: Ir-194 is used for portable imaging devices.

Fe-55 decays by electron capture with a half-life of 2.7 years. The capture of an electron by the nucleus leaves a low lying empty electronic K-shell which gets filled by another electron from a higher shell. This electronic transition leads to the emission of an x-ray of 5.9 keV energy and no hard (i.e., high energy) gamma ray. Fe-55 is used in portable x-ray sources that can last for a long time and can be used for many applications including x-ray fluorescence spectroscopy which is valuable for chemical or elemental analysis. Two other radioisotopes (Co-60 and Cs-137) are used in many industrial applications such as the sterilization of foods and medical supplies, the treatment of sewages, the processing of various chemical reactions, etc.

Moreover, radioisotopes are also used for online gauging to determine thicknesses of assembly components, fluid levels and so on as part of factory operations.

## AGRICULTURAL AND ENVIRONMENTAL APPLICATIONS

Tracer radioisotopes play an important role in helping understand the pathways and distribution of agricultural chemicals [8] and environmental pollutants [9]. They yield clues that help unravel interactions between soil, water, plants and animals and between air, water, and environmental health as well as their impacts on climate.

Radioisotopes like Ca-45, Mg-28, P-32 and Fe-59 have been used in plant nutritional studies. These are chemically indistinguishable from the corresponding stable elements and do not cause significant radiation damage. Soil contains the essential elements for

plant growth. Soil content is often supplemented with fertilizers for extra nutrients and with water for irrigation. Radioisotopes are used to monitor nutrient pathways and have been used to develop effective methods of farming. Chemical properties of soils and their nutrient contents can be related to plant growth. Moreover radiation has also been used to sterilize soils by eradicating microorganisms in plant nutrition studies; some of these microorganisms are harmful to plant life while others contain necessary enzymes for plant growth.

Radiotracers are also used for environmental studies and hydrological monitoring. Radioisotopes like H-3, C-14, S-35 and Cl-36 have been used to follow the distribution of combustion products (such as CO<sub>2</sub>, SO<sub>2</sub>, Cl<sub>2</sub>, etc) in the environment. Radioisotopes like Pt-191, Pd-193 and Ir-192 have been used as tracers to follow the fate of precious metals in sea water.

### **OTHER RADIOISOTOPE USES**

A few other practical applications of radioisotopes are included here [10]. Smoke detectors work either by optical detection (light sensing mode using the photoelectric effect) or by ionization. In this second mode, charged particles emitted by a radioisotope keep a constant current flow between two electrodes inside an ionization chamber. Smoke particles that enter the ionization chamber absorb the charged particles thereby stopping the current flow; this sets off an alarm. The Ni-63 radioisotope is used in ionization chamber smoke detectors. It uses a 10 micro curies source and emits betas (electrons) with a long half-life (100 years).



Figure 5: Smoke detector that uses Ni-63 beta source

Radioisotopes that emit charged (beta or alpha) particles are used as sources of electrical current when other forms of electrical supply are not adequate. The heart pacemaker is an implanted medical device that uses electrical pulses to regulate the beating of the heart. This device is used when the heart muscle contraction becomes irregular or abnormal. It is powered by a long-lasting battery and contains electrodes that are placed in direct contact with the heart muscle to stimulate regular beating. Heart pacemaker implantation

requires invasive surgery. In order to avoid frequent further surgeries to replace the batteries, low-power generators using radioisotope are implanted. A constant low-intensity electrical current is maintained by the continuous emission of charged particles (beta and alpha particles). For example, the Pu-238 radioisotope provides a convenient low power supply for some heart pacemakers. Pu-238 is an alpha emitter with a very long half-life (88 years).

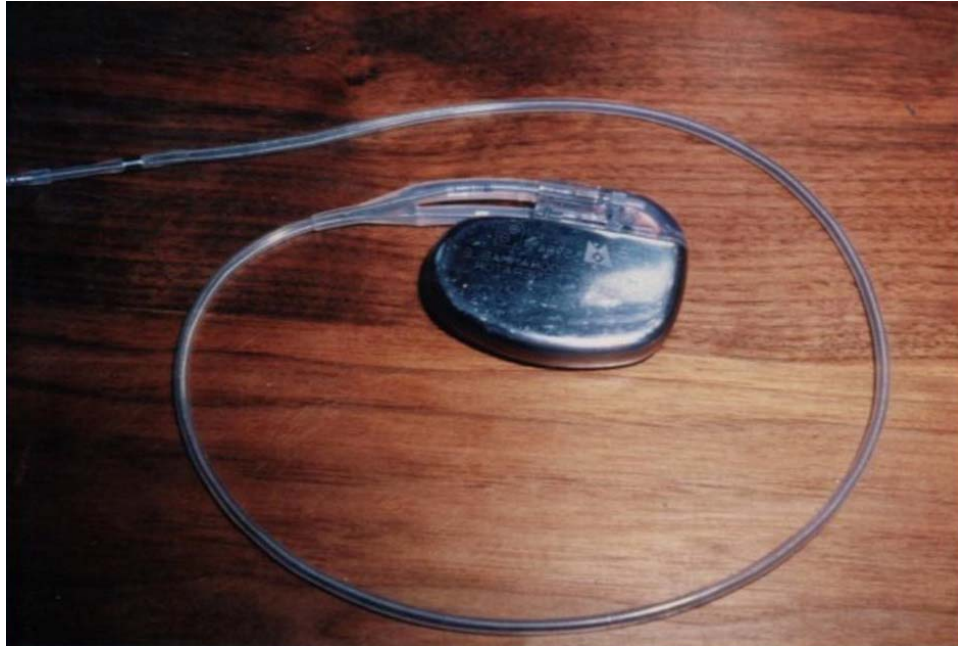


Figure 6: Some heart pacemaker are powered by Pu-238 beta source

Polonium was discovered by Marie Curie and named for her native land of Poland. The Po-209 radioisotope decays by emitting alpha particles with a long (102 years) half-life. This radioisotope is used in ionizing air guns to control static electricity and remove dust from product containers. However, it is highly toxic and must be handled with care.

In conclusion, radioisotopes have found wide uses in many applications. One such radioisotope (Co-60) is used in so many applications that it deserves a chapter of its own.

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9. Google search using the following keywords “environment” and "examples of radioisotope applications"
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## COBALT-60 APPLICATIONS

The cobalt radioisotope Co-60 gets used in so many applications that it has been upgraded to a chapter of its own. After introducing the Co-60 transitions, a few of these applications are described. These include food irradiation, sterilization of medical supplies, sewage treatment, enhancement of chemical reactions, reduction of pest infestation by suppressing their immune system, etc.

### THE CO-60 DECAY SCHEME

Co-59 is a stable isotope. Upon neutron capture it forms Co-60 which is a radioisotope. Metastable Co-60m decay into Co-60 by emitting a soft (low energy) gamma ray. Co-60 decays into Ni-60 by emitting two beta particles and two gamma rays [1]. The probability for the emission of the second beta is low. The emitted radiation is used extensively in many practical applications. The 5.27 years half-life for the decay of Co-60 means that the source has to be replaced every few years. Typical activities for Co-60 facilities vary between 1 Krad and 100 Krad depending on the use. Note that 1 rad corresponds to an energy deposition of 100 ergs in 1 g of material.

There are two unit systems, one is based on the centimeter-gram-second (CGS system) and the other (internationally used) is based on the meter-kilogram-second (MKS system also referred to as the SI units). The unit of energy in the CGS system is the erg while in the MKS system it is the joule (1 joule =  $10^7$  ergs).

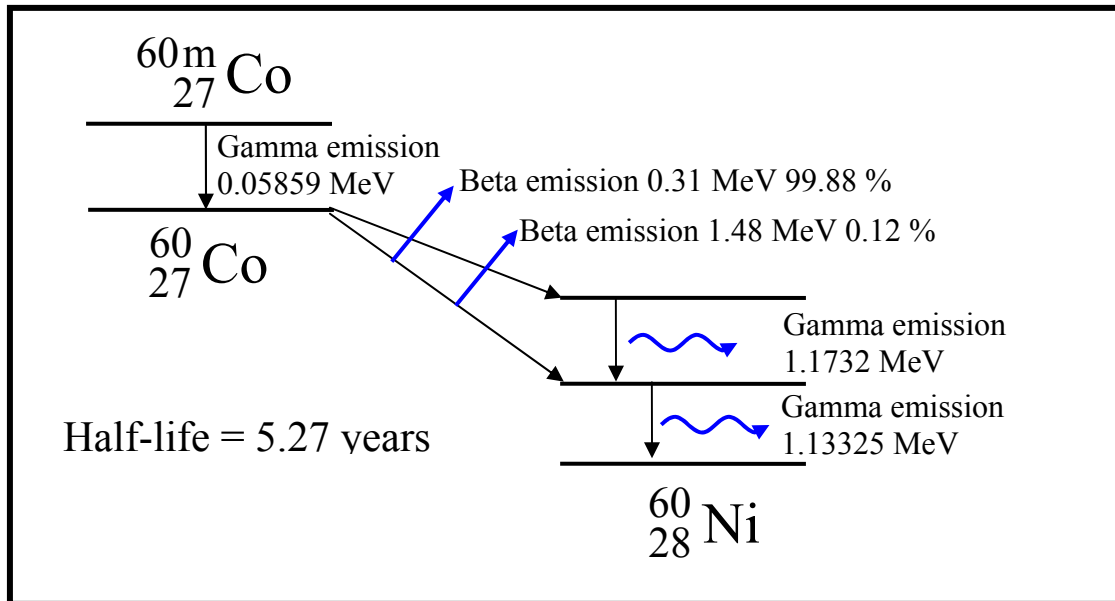


Figure 1: Decay scheme for the Co-60 transitions showing beta or gamma emissions, the energy of the emitted radiation and the probabilities.

## FOOD STERILIZATION

Food sterilization is undertaken to enhance preservation and increase storage time of various foodstuffs. Conventional food preservation methods include the drying of fruits, the freezing and pickling of vegetables, the salting and smoking of meats, etc. The spores that can cause spoilage are sometime unaffected by these traditional food preservation methods. Food treatment through exposure to ultraviolet radiation works better in some cases but tends to change the color, flavor and texture of food. Food irradiation [2,3] kills microorganisms and insects in the food, inhibits sprouting and delays ripening by slowing down growth.

Food irradiation is permitted in over 40 countries in the world. The US Food and Drug Administration approved the irradiation of wheat and potatoes in the 1960s, of spices, some fruits and vegetables in the 1980s, and poultry and meat products in the 1990s. Food irradiation helps reduce the use of pesticides and fumigants, extends shelf life and is lower cost. Radurization (term used to denote the radiation treatment of foods) can be applied to completely packaged products moving on a conveyor belt. The appellation “cold pasteurization” is also used. Astronauts and recipients of organ transplants rely routinely on irradiated foods. Some common folks, however, are unwilling to try irradiated foods. Opponents of food radurization argue that radiation that helps preserve food also eliminates the odors and obvious spoilage texture that warns about spoiled food thereby increasing the chances of food poisoning. They also maintain that radiation can also create cancer-causing chemicals such as benzene or formaldehyde found in irradiated foods.

Irradiated foods are marked with a distinctive international “radura” logo [4]. Some irradiated foods are readily available in supermarkets such as strawberries from Florida or pineapples from Hawaii. Irradiated ground beef is sold in 16 states. Some irradiated spices have been in supermarkets for many decades. Most supermarket food chains have, however, taken a wait-and-see stance hoping that consumers will start eagerly purchasing irradiated food products because these last longer. A potato irradiation plant has been operating in Japan since the 1970s; it uses a 150,000 curie Co-60 source and irradiates over 40,000 tons per year to prevent sprouting and increase the shelf life by several months. It should be noted that irradiated foods are not radioactive and are therefore safe to consume. Thousand of supermarkets and retail stores sell irradiated foods but the market is growing very slowly. Global consumption of irradiated foods has however not taken place.

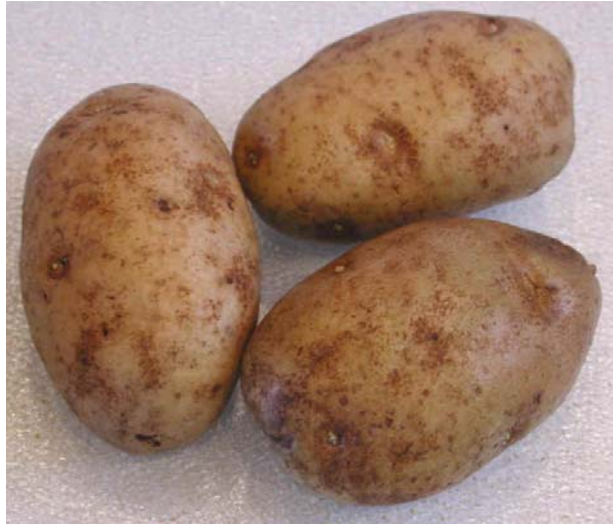


Figure 2: A plant irradiates 40,000 tons of potatoes in Japan. The international radura symbol is displayed on irradiated food labels.

## CO-60 MEDICAL APPLICATIONS

The first Co-60 application that comes to mind is radiation therapy for various forms of cancers. Co-60 has a convenient half-life (5.27 years) and reasonable gamma energies (around 1 MeV) and is used in some hospitals for cancer therapy. The first such treatment was undertaken in 1951. Cancer treatment consists in aggressive chemotherapy and radiation therapy. Standard irradiation facilities use an extended gamma source (2 cm by 5 cm in size) for which the applied dose is not uniform making the edge of the irradiated area fuzzy; this is referred to as the penumbra effect. The Co-60 source is renewed every few years. Some 100,000 new cancers are diagnosed every year around the world, most of which receive radiation treatment. Co-60 units are well suited for the treatment of head, neck and spinal cord cancers that are close enough to the skin that they can easily be reached by the radiation. Other forms of cancer (like cervical, oesophagus, lung, prostate, etc) are still treated using Co-60 sources but their deep location in the body (more than 20 cm deep) endangers exposure to other organs. It is estimated that at least 1 Co-60 unit per million population is needed even in developing countries. Presently, the US has 12 units per million, China has 0.3 units per million and some 30 countries have none. An alternative form of irradiation uses linear accelerator units that can deliver well-collimated x-rays as well as electron beams. These are increasingly used to replace Co-60 sources.



Figure 3: The Co-60 cancer radiation therapy machine.

The so-called “gamma knife” [5] uses a very compact Co-60 source to treat localized areas of the brain (with “surgery” precision). This form of localized radiation treatment is required for patients diagnosed with brain metastases. Some half a million patients have been treated so far with gamma knife procedures in the US.

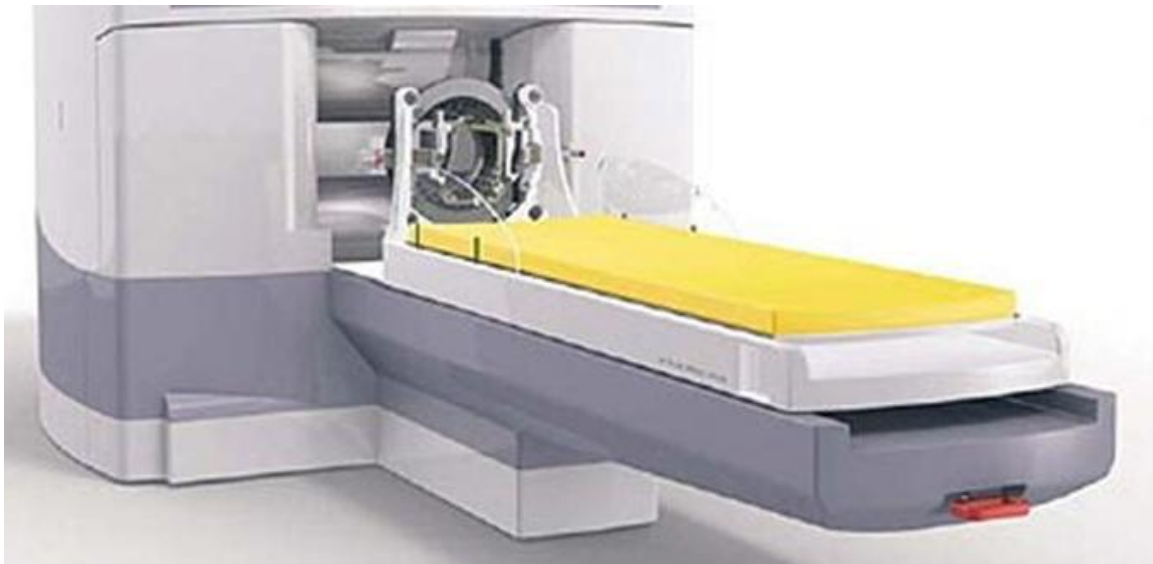


Figure 4: The “gamma knife” is used for localized radiation treatment of the brain

Another Co-60 application is in the sterilization of medical supplies such as cotton balls, surgical gloves, syringes and bandages. Such sterilization facilities have been in use for over 30 years; over 100 of them are operating in the US. This sterilization method is replacing the former practice of using ethylene oxide gas (which is toxic) for sterilization.

## **OTHER CO-60 APPLICATIONS**

Co-60 irradiation is also used in many other applications. It is used to sterilize household items such as baby pacifiers, packaging stuff, cosmetics, etc. Non-stick cookware coatings are enhanced through irradiation. Tires are irradiated to increase their durability. Irradiation sources are used to perform security checks on luggage at airports.

Co-60 irradiation reduces pest infestation. Each year between 10 % and 25 % of crops worldwide are lost to insects and other pests. Irradiation induces chromosomal mutations in pests thereby affecting wider populations over many generations. Huge populations of insects are bred, irradiated to knock out their immune system then released in infested areas in order to decimate that population. This technique has been applied to the fruit fly in Argentina and Chile, to the screwworm in Mexico and the southern US and to the tsetse fly in parts of Africa. For example, a small dose of 700 rads is enough to inactivate the immune system in mice. Radiation is also used to kill endophyte bacterial fungus in hay fescue used as animal feedstock.

Co-60 irradiation inactivates microorganisms in domestic sewage thereby transforming it into useable compost or fertilizer. It causes damage to the DNA makeup of bacteria. Small irradiation doses permit the dehydration of sewage thus decreasing its volume. Many sewage treatment plants exist around the world including at Boston and Munich. UV irradiation is an alternative sewage treatment method.

Irradiation is used for genetic modification of plants making them more productive or more resistant to pests. Irradiation is also used for the sterilization of some products before they are exported to other lands. For example, wood and raw wool products are irradiated before leaving Australia.

Co-60 irradiation is used to enhance the reaction yields of some chemical process of industrial relevance. A conventional method for enhancing yields in chemical reactors is through increased temperature and pressure. This method is more costly. Irradiation favors the population of excited atomic states which helps some chemical reaction routes. Dow Chemical operates an ethylbromide production plant that uses Co-60 irradiation in Michigan. It produces one thousand tons of this chemical per year.

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## NEUTRON RADIOGRAPHY

The terms imaging and radiography are often used interchangeably. Radiography is used when x-ray sensitive films are used to record images while imaging is used when high resolution 2D cameras are used instead. In both cases, a scintillator converter plate is used between the radiographed object and the recording device. There are many applications of neutron radiography [1] when x-ray radiography is not sensitive enough.

### X-RAY AND NEUTRON RADIOGRAPHY

Everyone is familiar with x-ray imaging or radiography. Neutrons can be used for imaging purposes as well. Neutrons and x-rays are sensitive to the various elements in different ways. For x-rays, heavier elements are more opaque while for neutrons this is not the case. For example, hydrogen-containing materials (such as plastics or aqueous fluids) are completely transparent to x-rays but are opaque to neutrons and can therefore be easily resolved. Both x-ray and neutron radiographs are obtained in black-and-white only. Colors are sometime added after an image has been recorded.

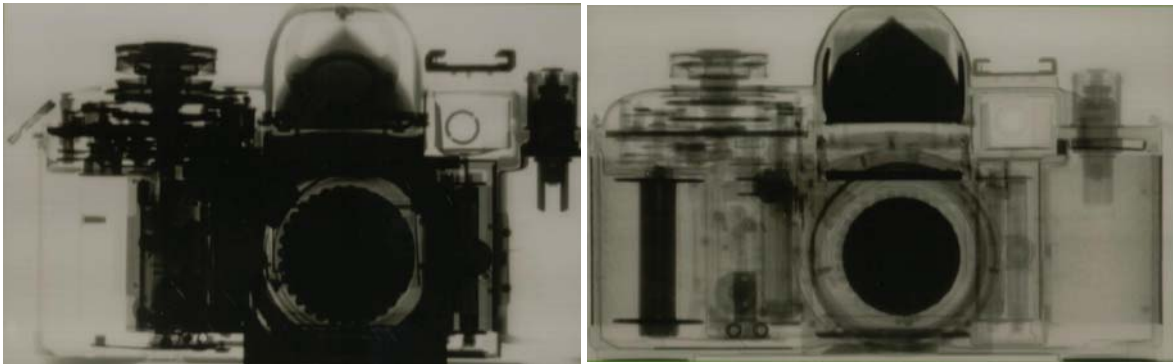


Figure 1: X-ray radiography (left) and neutron radiography (right) of a camera.

The attenuation of an x-ray or neutron beam is characterized by the transmission factor defined as the ratio of the transmitted intensity through the sample to the incident intensity (measured without the sample). The thickness of various materials for 50 % transmission is compared for x-ray and neutron attenuation assuming a  $1.5 \text{ \AA}$  wavelength in each case.

Table 1: Thicknesses of various materials for the attenuation of x-ray or neutron beams by 50 %

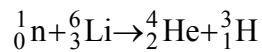
Element	Thickness for 50 % Neutron Transmission	Thickness for 50 % X-Ray Transmission
Carbon	1 cm	$7 \cdot 10^{-2} \text{ cm}$
Aluminum	7 cm	$5 \cdot 10^{-3} \text{ cm}$

Titanium	1.5 cm	$7 \times 10^{-4}$ cm
Vanadium	1.25 cm	$5 \times 10^{-4}$ cm
Tungsten	0.66 cm	$2 \times 10^{-4}$ cm

This table shows that neutrons are more penetrating than x-rays and can reasonably “see” a wide range of elements.

## NEUTRON IMAGING

The technique of neutron imaging relies on the use of high resolution neutron detectors. Neutron scintillation detectors use a good neutron absorber (such Li-6) which produces two charged particles (He-4 and H-3).



The charged (alpha and triton) particles are stopped in ZnS material mixed to Li-6. ZnS emits blue light. Mixing Cu, Al and Au to the scintillation material produces green light. A low light (CCD) camera is used to produce a digital image. This uses the photoelectric effect whereby incident photons get converted to electrons which get amplified by an applied voltage.

The scintillator (also called converter) plate is some 300 microns thick; this determines the resolution of this technique. Thinner plates can be used but capture a lower flux of neutrons thereby taking longer time to capture the image.



Figure 2: Photo of a scintillator (converter) plate used for neutron imaging. Absorbed neutrons produce emitted green light.

Note that the same technology is used to produce night-vision goggles whereby low infrared light levels are converted to an image which is projected onto a small screen on the goggles just in front of the eyes.

Neutron radiography is used to image internal (hidden) parts behind opaque (for example metal) plates. Neutrons can resolve hydrogen very well. Neutron images are taken of complex objects. Tomography consists in computer reconstruction of the details of the 3D object including its internal structure from the various individual 2D images.

There are various forms of neutron radiography. (1) Still radiography is the simplest and consists in taking the radiograph of an object. (2) Dynamic radiography is used to image moving parts or fluids inside closed systems like car engines. (3) Stroboscopic radiography is used to “freeze” various phases of a periodic motion such as one of the four cycles of a combustion (car) engine. These cycles are the intake, compression, power and exhaust stages. Stroboscopic radiography involves a means of recording the image as well as gating of the detector system to the observed periodic motion. (4) Resonance neutron radiography uses monochromated neutrons of specific energies that correspond to known resonance absorption energies for specific atoms or isotopes in the sample. Resonance radiography can be used as a non-destructive high temperature thermometer that can measure in the window between 1000 K and 3000 K with a precision of 10 K. This method is based on the known variation of the resonance energy width with temperature. Another application of neutron resonance radiography is in detecting explosives concealed in checked luggage or cargo. It uses the resonance neutron absorption cross section for oxygen, nitrogen, carbon and hydrogen (main constituents of explosives). Some of these radiography methods can be performed in low neutron flux environments while others (like the dynamic and stroboscopic methods) require high flux neutron beam tubes. Spatial resolution can be enhanced by using tight neutron collimation before the radiographed object.

Scintillator (converter) plates containing other neutron absorbers such as gadolinium oxide are also used. The imaging medium can also be a metal foil (such as indium or dysprosium) that can be activated in order to produce a radioactive image upon neutron exposure. This image can be later transferred to an x-ray film away from any gamma background; this technique is called transfer radiography. This method is rarely used because it takes longer to process the image and is more costly.

## **IMAGING OF HYDROGEN FUEL CELLS**

As the cost of crude oil (and thereby gasoline) increases, more and more efforts are made to find alternative sources of fuels [2]. These include bio-diesel and ethanol fuels obtained from corn, sugarcane and switch grass as well as hydrogen fuel. Hydrogen is what fuels space rockets (like on the space shuttle) and (it is hoped) will provide much of the fuel needed for cars and trucks in the future. Bio-diesel fuels burn in car engine. Hydrogen is used to generate electricity in fuel cells.

Fuel cells use an entirely different technology than the internal combustion engine. Hydrogen fuel is channeled to the anode on one side while ambient oxygen is fed to the cathode on the other side of a fuel cell. At the anode, a catalyst causes hydrogen to get ionized into protons and electrons. A membrane allows only the protons to pass through to the cathode. The electrons, on the other hand, travel along an external circuit thereby creating an electrical current. Current hydrogen fuel cells can achieve close to a volt but can be stacked to achieve higher voltage capacity.

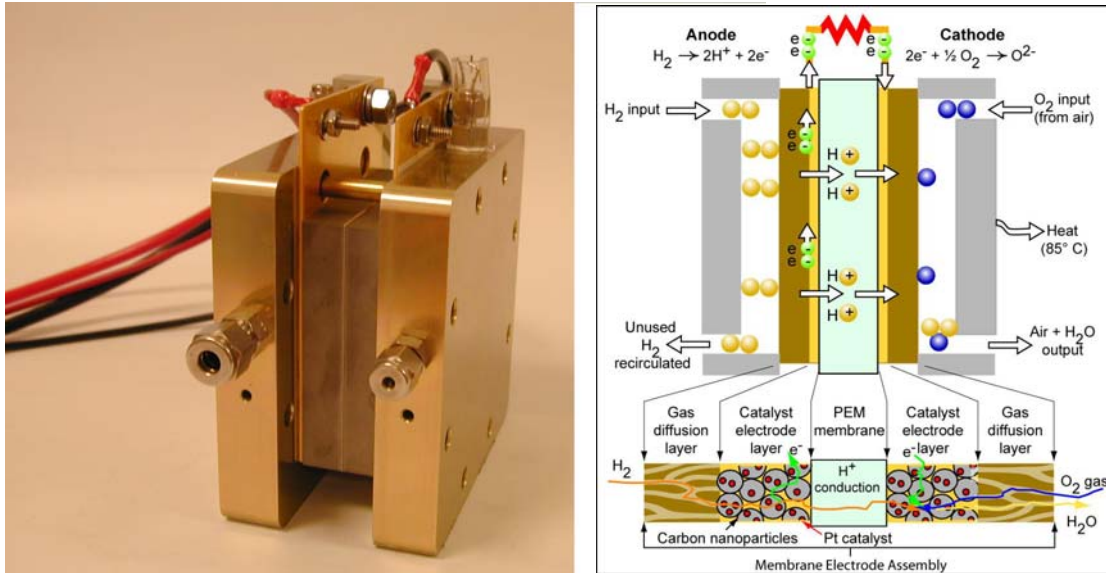


Figure 3: Photo of a hydrogen fuel cell (left) and schematics of its various parts (right).

Neutron imaging has played an important role in the diagnostics of the proton exchange membrane fuel cell; it is the only in-situ method for visualizing water content and distribution inside an operating fuel cell. For example, liquid water was found to accumulate near the anode layer, contrary to customary assumptions. This may be due to the local heating of the anode. The former (almost primitive) method of obtaining comparable information was to freeze an operating fuel cell in liquid nitrogen then saw it open to map the frozen water content inside. Note that all forms of radiography produce black-and-white images only. Image digitization allows the mapping to a color scale from the recorded grey scale.

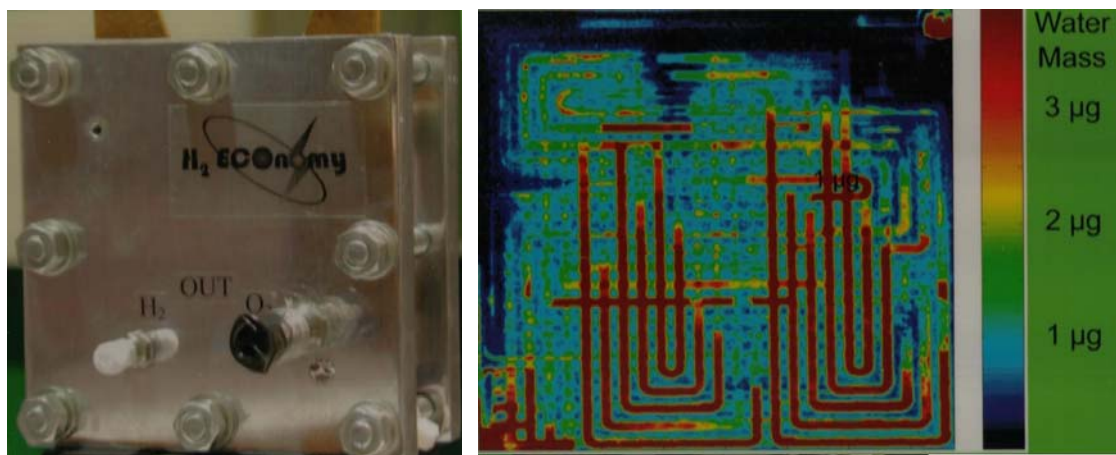


Figure 4: Photo of the end plate of a hydrogen fuel cell (left) and neutron image showing water circulation inside (right). Colors were digitally added to the recorded black-and-white image.

## OTHER APPLICATIONS OF NEUTRON RADIOGRAPHY

A few other applications of neutron radiography are included here. This technique is used to visualize cracks, voids, or bubbles inside various metallic structures that cannot be visualized using x-rays. Moreover neutron radiography is apt at detecting corrosion in aluminum structures since corrosion is an oxidation process involving aluminum hydroxide  $\text{Al}(\text{OH})_3$  containing lots of highly visible hydrogen. Internal condensation and fluid flow can be visualized inside metal tubes. The inner workings of complex machines can be diagnosed. These include car engines, carburetors, espresso coffee machines, hydraulic systems driving robots used in assembly lines, turbines, aircraft components, etc.

Neutron radiography has also been used for scientific studies investigating water intake in vegetation, the phases of germination in plants, and so on. Furthermore, this technique has found effective use in archaeological investigations. In one instance, the internal contents of Egyptian (pharaonic) bronzes shaped in the form of birds were found to actually contain birds' skeletons inside. Bronze is opaque to x-rays but fairly transparent to neutrons. In another instance, early Chinese bronzes were found to contain grains, nuts and special fibers. These are special cultural symbols representing life. It is noted that the value of such religious and cultural symbols would not have permitted the opening of such artifacts making neutron radiography the only way of peeking inside.

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## NEUTRON GAUGING

Neutron gauging consists in monitoring the attenuation of incident neutrons while crossing materials. It is also used to probe hydrogen content through enhanced neutron scattering. Neutron gauging has many applications in mining operations, well logging, and bulk process streams.

### MINING AND WELL LOGGING OPERATIONS

Neutrons are routinely used in mining and well logging operations [1]. Since neutrons are very sensitive to hydrogen, they can detect hydrogen rapidly and unequivocally. A small neutron source is lowered into a drilled hole. Compact neutron sources consist in alpha particle emitters (such as Am-241) surrounded by beryllium (which absorbs an alpha particles and emits neutrons). Neutrons can also be produced using small linear particle (mostly proton) accelerators through the (p,n) reaction. Such Van de Graff neutron sources can be as small as 10 cm in size. Such compact neutron sources are lowered into holes bored for mining or well logging. They can survey rock and mud content in strata. Back scattered neutrons are measured along with gamma rays emitted following neutron capture. A spike in hydrogen content deep into the hole or well is a sign of oil, water or natural gas bearing rocks.



Figure 1: Neutron gauging is used in well logging to survey deep strata.

## **INDUSTRIAL AND RESEARCH APPLICATIONS**

Neutrons are also used in gauging and control processes in industrial operations. These include the sorting and grading of ores under bulk handling condition (such as on a conveyor belt), the real time analysis to determine the sulfur and moisture content (for example), the monitoring of moisture content in concrete and other rapidly drying materials, etc. Neutron transmission and scattering cross sections are also sensitive to voids and porosity in most media. These are used for quality control of the thickness of various manufactured products as they pass through a conveyor belt.

Hydrogen has the highest incoherent neutron scattering cross section making it unambiguously detectable and its amount quantifiable. Precise neutron transmission measurements can for instance determine the carbon-to-hydrogen ratio in hydrocarbons. This ratio is referred to as the cracking ratio and is one of the figures of merit for classifying crude oils. Cracking refers to the breaking up of long oil macromolecules into useable fuels and petroleum products. The hydrogen fraction is adjusted in order to tune the produced monomer feedstock. Monomers (like ethylene, propylene, etc) are the raw material feeding the entire plastics industry. This ratio can be determined down to a fraction of a percent. Moreover, the relative fraction of hydrogen-to-zirconium (Zr) is determined down to parts per million in the manufacture of the cladding that hold nuclear fuel rods.

The hydrogen-to-nitrogen ratio in various nuts, grains and other foodstuff determines their nutritional value. This ratio is used in research studies. The nutritional value is defined in terms of the number of calories per serving. A serving corresponds to a 100 gram portion (3.6 ounces). Nutritional value is also related to the content in water, carbohydrate, fat, protein, sugar, vitamins and minerals. For example, the moisture content has been investigated in bulk powdered foods and in army food rations.

In another study, the stud quality of coniferous lumber was correlated to moisture content.

Note that the Mars Science Laboratory rover mission carried a neutron detector instrument (called Dynamic Albedo of Neutrons or DAN for short) used to identify the presence of water near the Mars surface (down to 1 m depth) [2]. The neutron albedo of a substance characterizes how strongly it reflects neutrons. It turned out that proving that water exists on the Mars surface was easy to accomplish. The rover robot arm dug slightly deep and scooped some soil sample that contained white substance. This substance could have been either minerals or ice. Seeing that it melted when exposed to sunlight increased the odds that it was water. Other tests confirmed that finding.

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## NEUTRON DEPTH PROFILING

### THE NEUTRON DEPTH PROFILING TECHNIQUE

Neutrons are absorbed by many nuclei. Neutron absorption is often accompanied by the emission of two nuclei (charged particles) with specific kinetic energies. These charged particles slow down while ionizing atoms in their surrounding. The remnant kinetic energy of each of these charged particles when it leaves the surface of the material is a measure of how deeply seeded it was at birth. Measuring such exit kinetic energies yields the depth profile of the absorption site and therefore the distribution of the neutron absorber close to the material surface. Many nuclear reactions are used for Neutron Depth Profiling (NDP).

Table 1: Nuclear Reactions used in Neutron Depth Profiling.

Reaction	Cross Section (barns)	Abundance	Heavy Particle Energy (keV)	Light Particle Energy (keV)
Li-6(n, $\alpha$ )H-3	940	0.075	2728	2056
B-10(n, $\alpha$ )Li-7	3837	0.199	840	1472
N-14(n,p)C-14	1.83	0.996	42	584
Cl-35(n,p)S-35	0.489	0.758	17	598

### NEUTRON DEPTH PROFILING FACILITY

A thermal or cold neutron beam is incident upon the investigated neutron absorbing sample. Each neutron absorption releases two charged particles, a light one (proton or alpha particle) and a heavier one (depends on the nuclear reaction used). The light particle carries most of the kinetic energy [1]. Charged particle detectors are used to record the kinetic energy profile of the exiting charged particles. Charged particle detectors use a bias voltage between an anode and a cathode to sense the electron-ion pairs. The silicon surface barrier detector is one such charged particle detector. The sample and detectors are placed inside a high vacuum chamber.

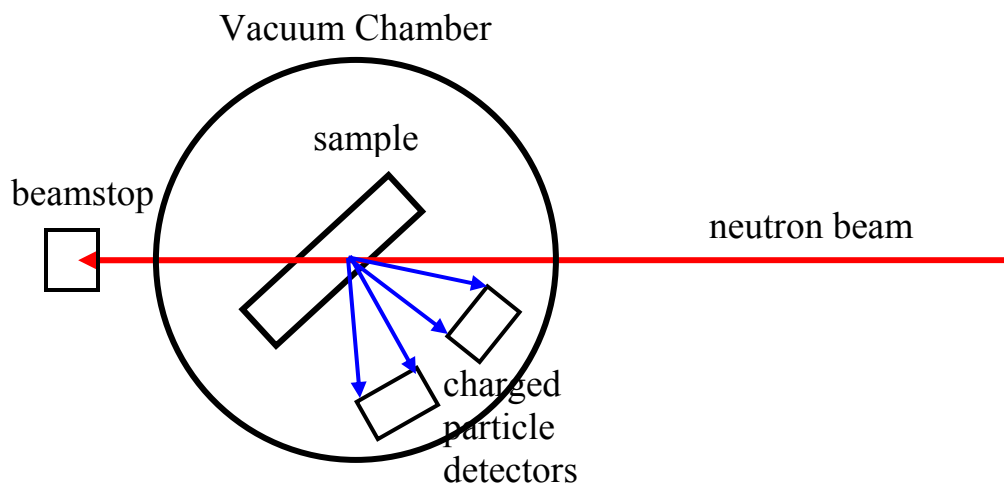


Figure 1: Neutron Depth Profiling geometry.

A Neutron Depth Profiling facility is in operation at the NIST Center for Neutron Research [2-4]. It uses cold neutrons and is located on neutron guide NG1.

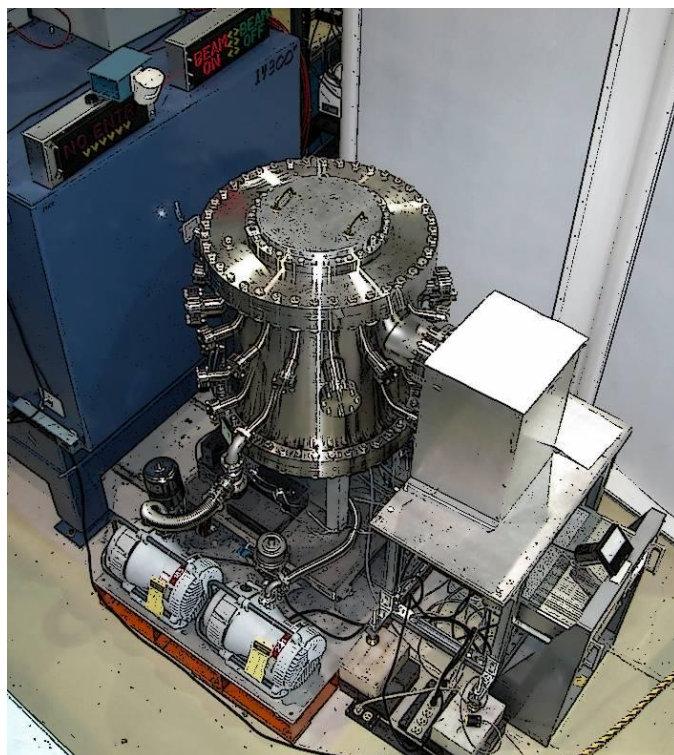


Figure 2: The Neutron Depth Profiling chamber at the NIST Center for Neutron Research.

The nuclear reaction  $B-10(n,\alpha)Li-7$  is often used to map out the boron depth profile inside materials such as silicon semiconductors. Natural boron has 20 % abundance in B-10. Since the path lengths of charged particles (alpha particle and Li-7 in this case) are

very short in solid samples, the NDP technique is sensitive to shallowly seeded boron and can map out skin depths in the micron range with a few nanometer resolution. The alpha particles ( $\text{He-4}$  nuclei) are emitted with a kinetic energy of 1.472 MeV and the  $\text{Li-7}$  nuclei are emitted with 0.84 MeV kinetic energy. Since the incident (thermal or cold) neutron has very small kinetic energy (meV range), the two charged particles are emitted in opposite directions and isotropically.

## NEUTRON DEPTH PROFILING APPLICATIONS

Two NDP B-10 profiles are shown for two samples, one where the boron layer is thin and very close to the surface and another one containing a thicker boron layer. Boron is used as dopant in silicon semiconductor devices where it is implanted. Silicon is an insulator. Doping it with (implanted) boron makes it a p-type semiconductor (i.e., an electron receptor). Mapping out the boron distribution in such semiconductors helps adjust the implantation process. Note that once a charged particle has slowed down entirely inside the material, it does not get out and can not therefore be detected. This constrains the detected signal to be within an energy window for each of the charged particles.

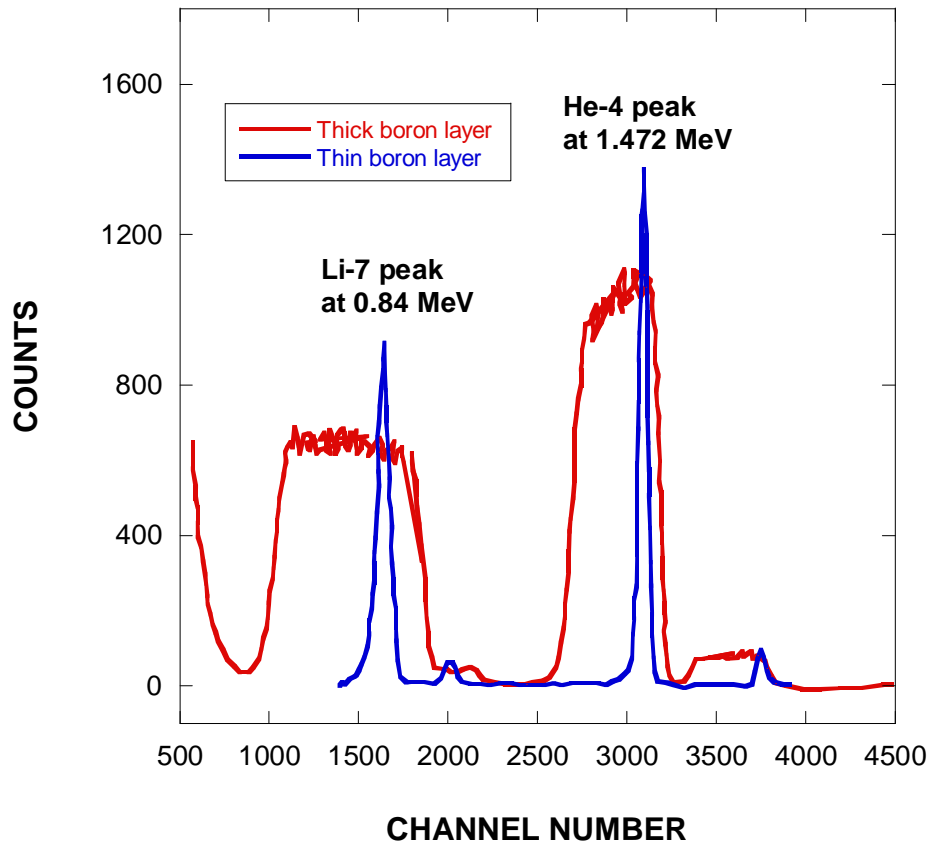


Figure 3: Neutron Depth Profiling for B-10 content in two samples with different boron layer thicknesses. The energy (x-) axis is given in arbitrary channel numbers.

The number of detected (charged particle) counts observed at a sample depth is proportional to the concentration of the neutron absorbing nuclide at that depth. Concentrations down to parts per million can be detected. The depth profile is obtained from the charged particle spectrum. Geometry corrections are included. Standard samples of known composition are used for calibration purposes. Note that little sample activation incurs upon neutron irradiation for NDP.

The NDP method has been used in many applications. Boron is added to dielectric phosphosilicate glass to increase its melting point and thereby minimize thermally induced diffusion. Phosphosilicate and borosilicate glass multilayers are sometime used to fine tune the dielectric properties. Lithium is sometime added to niobium to make optical waveguides. Lithium distribution and loading have been investigated in lithium batteries.

One such application is described here. Electrochromic materials transmit different color light when a different voltage is applied. These have found applications in color-changing windows and optical filters. They use lithium ions which help transmit different light colors when a different voltage is applied. . NDP has been used to determine the distribution of lithium ions in electrochromic material. Using multilayers help the fine tuning of such material. NDP showed that varying the applied voltage changes the lithium distribution and that this process is reversible.

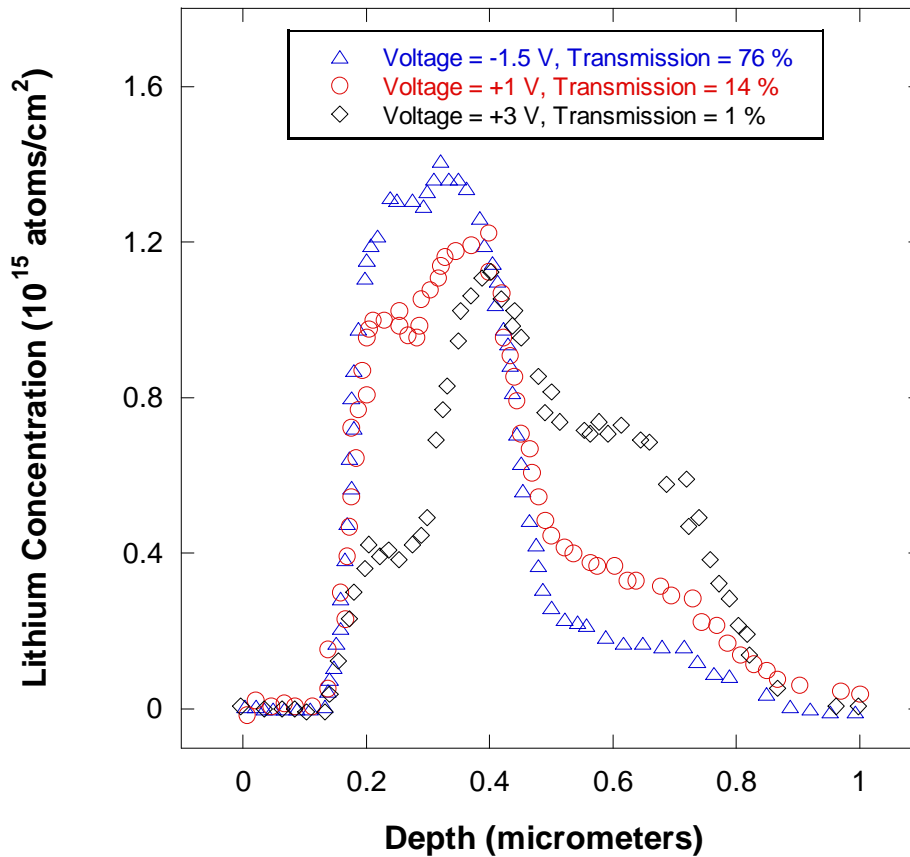


Figure 4: Lithium transport in electrochromic multilayer films showing the lithium concentration as a function of the applied voltage and the resulting effect on the optical transmission of the films.

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## **NEUTRON PROCESSING**

Epithermal and fast neutrons produce transmutations (nuclear reactions) as well as radiation damage. Radiation damage refers to the local displacement of atoms from their lattice sites. Radiation damage has a mostly negative connotation, but has found many useful applications [1] such as in track etching, the coloration of gemstones, the doping of silicon to produce semiconductors, and the hardening of metals used for drilling. Neutron cancer therapy could also be included in this category since it involves the destruction of cancerous cells in patients receiving therapy. These useful applications of radiation effects are referred to as neutron processing.

### **TRACK ETCHING**

Fission releases neutrons as well as two fission fragments. These are heavy elements with broad mass distributions. These fission fragments produce tracks (or damage trails) when they cross materials. These tracks have several applications.

Fission fragment tracks are used to date rocks and geological formations. The most abundant isotope in natural uranium is U-238; U-238 fissions spontaneously at a minute but finite rate with a half life of 4.5 billion years. Each fission reaction leaves a track. Using neutron activation analysis to quantify the amount of U-238 in a geological material and counting the number of tracks yields the age of that material over billions of years time scale [2].

U-238 tracks were used to date the eruption of a super volcano some 75 thousand years ago. This was a gigantic eruption a thousand times larger than any other one in recorded history. This event was correlated with a spike in sulfur levels observed in ice core data obtained from ice drillings close to the North Pole. This spike in sulfur levels was identified using neutron activation analysis and occurred some 75 thousand years ago as well. The third piece of evidence consists in a temperature drop by as much as 6 °C that took place at the same period and lasted for some 2 thousand years. A comparison of ashes collected from various volcanoes around the world pointed the location of the super volcano (also called mega volcano) to Lake Toba in Indonesia which erupted 75 thousand years ago. This was followed by a temperature drop around the world which started an ice age. There is some evidence of other super volcano eruptions around the world. For example, there is evidence that Yellowstone on the US was the site of a super volcano eruption some 2.1 million years ago.

The microporosity produced by fission tracks in uranium-doped glass is used to advantage in High Performance Liquid Chromatography (HPLC). HPLC columns are used to perform fractionation and measure macromolecular weight distributions. Dissolved polymers are fed to the top and slowly trickle down the chromatographic column. Shorter polymer chains dwell longer inside the pores and therefore diffuse

slow down the column. Longer molecular weight polymers reach the bottom of the column faster. Fractionation consists in separating the various molecular weights.

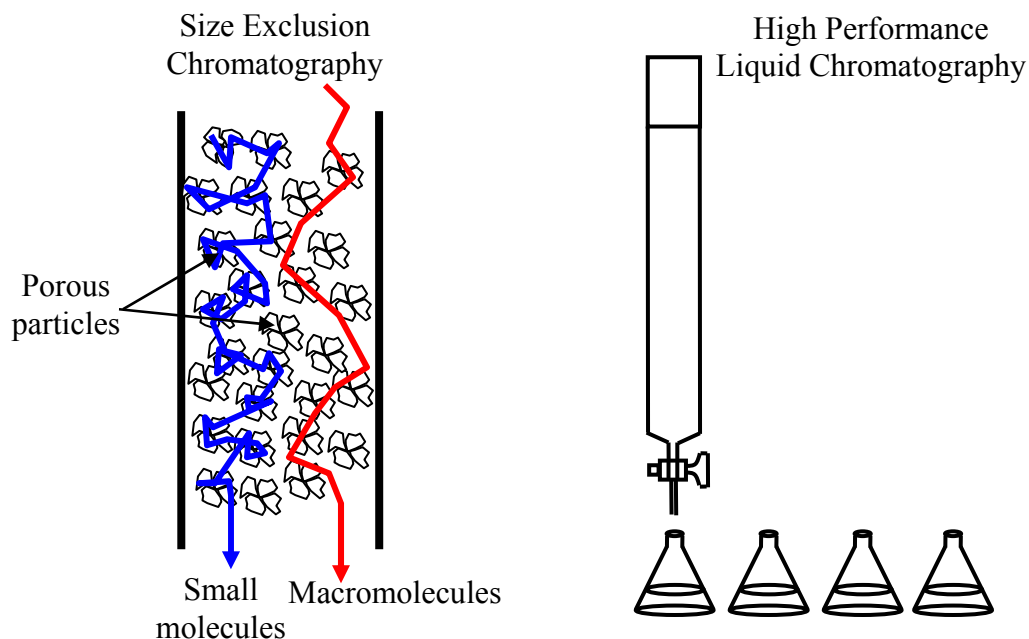


Figure 1: Chromatographic column.

Another useful application of track etching is the production of plastic filter material called Nucleopore for chemical and pharmaceutical applications. A thin polycarbonate film is made to pass next to a fissionable plate that produces fission fragment tracks. These are submicron pores in the film. Irradiation time controls the pore density while a subsequent chemical etching bath controls the pore sizes (in the micron range). The regular shape and controlled size of the pores make Nucleopore filters superior to conventional cellulose fiber filters. Nucleopore filters are used in microbiology where they are able to trap cells while removing all other fluids [3].

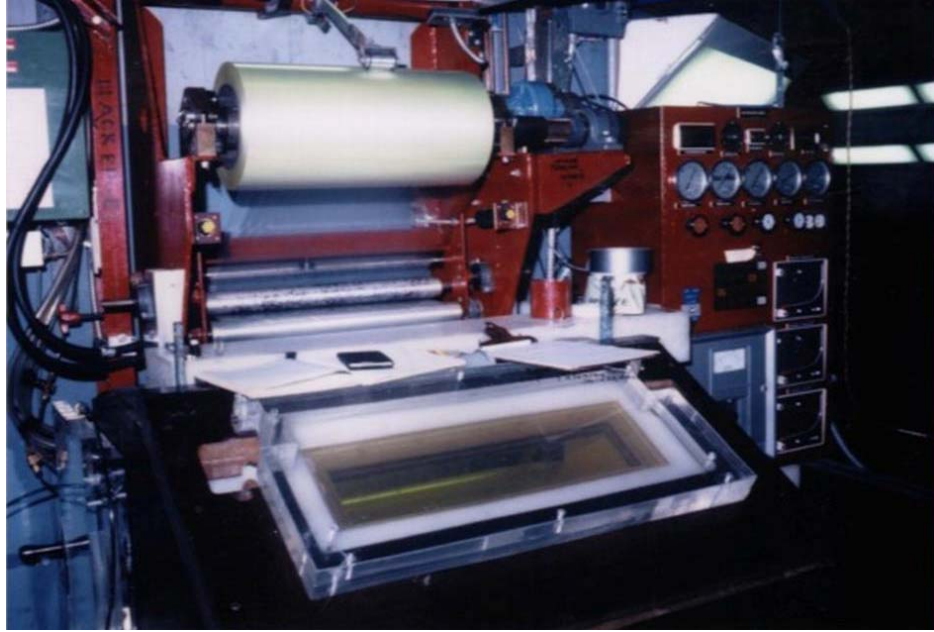


Figure 2: A roll of polycarbonate film is made to pass next to a fission plate at the University of Missouri Research Reactor. Fission fragments create uniform pores on the film changing it to filter material.



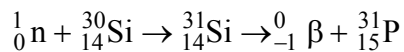
Figure 3: Nucleopore filters are widely used in laboratories and in industry.

## TRANSMUTATION DOPING OF SILICON

Silicon is the second most abundant element in the earth's crust after oxygen. It is obtained from sand (silicon oxide). Silicon is widely used as a semiconductor in the computer industry to make processor chips, to manufacture electronic devices such as transistors and integrated circuits. High purity silicon has also found uses in photonic (light emission) as well energy-storage applications. In conductors, electrical current is carried by electrons while in semiconductors, current is carried by electrons in one direction and positively charged "holes" in the opposite direction. Neutron irradiation of silicon single crystals changes the Si-30 isotope (3.1 % natural abundance) to P-31 which acts as electron donor making this material an n-type semiconductor.

Silicon semiconductors are pervasive in electronics and in the fabrication of computer chips. In order to explain the benefits of semiconductors, let's take the example of a simple diode. A diode is the stacking of an n-type (phosphorous doped) and a p-type (boron doped) semiconductors. A diode has the essential feature that it conducts electrical current only in one direction. The sandwiching of two diodes (pnp or npn sequences) makes a transistor. A transistor can act as a switch (transmit current in one direction) as well as an amplifier. An integrated circuit contains many electronics components (including transistors) integrated into a silicon chip. A computer chip contains a large number of integrated functions including switching; i.e., being able to write zeros and ones to encode digital data. Silicon revolutionized modern technology.

The transmutation doping nuclear reaction proceeds as follows.



This reaction produces beta particles with a half-life of 2.6 hours. Strictly speaking, this application does not involve radiation damage but rather nuclear transmutation. The silicon single crystals are produced by a high temperature float zoning process. Ingots as large as six inches in diameter can be produced. Neutron Transmutation Doped (NTD) silicon [4] has superior electronic performance than those containing implanted P-31 isotope (using accelerators). NTD silicon is used in many electronic devices such as power rectifiers, infrared detectors, diodes, transistors, solar cells, etc.



Figure 4: Ingots of high purity single crystal silicon produced by the float zoning crystal growth method. Such ingots are irradiated in nuclear reactors to produce semiconductor.

## **COLORATION OF GEMSTONES**

Neutron irradiation produces color centers in gemstones. This gives them an attractive artificial color. Color centers are defects in the crystalline structure that change the color of the material. Irradiation helps defect ions catch an electron thereby filling the empty electronic shell. This makes it absorb light in the visible range. Topaz turns from its original colorless or light brown character when it is mined to a nice blue color upon irradiation; this enhances its value. Topaz is mined in many parts in the world such as Australia, Brazil, India, Nigeria, and Sri Lanka. Many research reactors are used to irradiate Topaz as an income-producing service. After irradiation, Topaz is stored and allowed to decay to close to background radiation levels before being released to the market place. Over 13,000 pounds of Topaz are irradiated every year worldwide, some 40 % of which is done in the US. Irradiated Topaz has grown into a huge business venture involving wholesale and retail distribution companies all over the world. Its growth stems from the low prices of artificially colored Topaz.

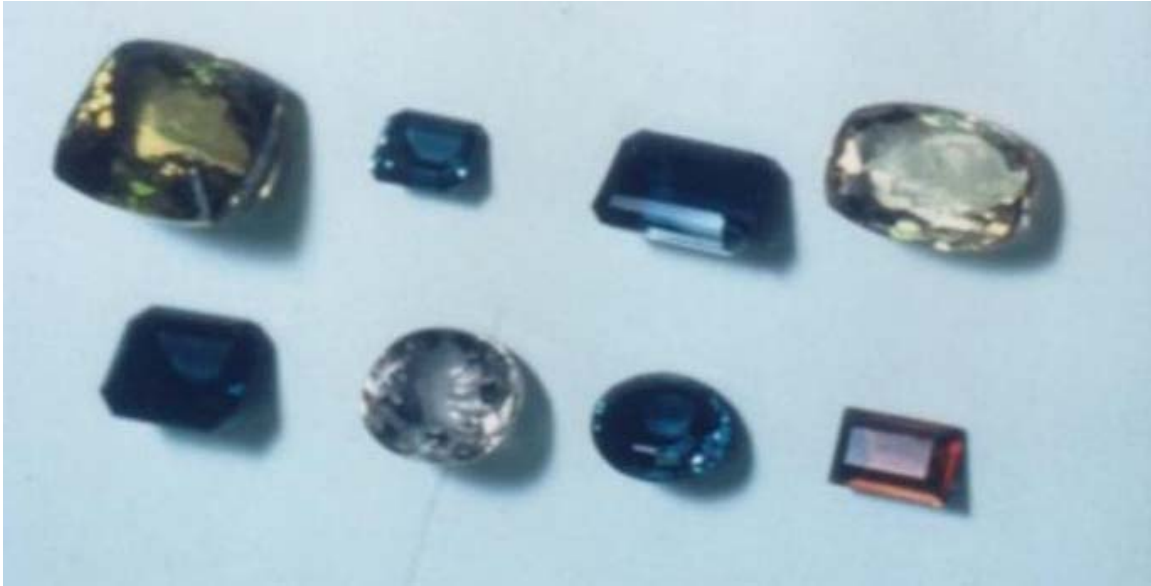
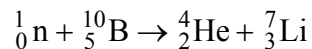


Figure 5: Pieces of irradiated gemstones. Topaz acquires a desired deep blue color.

## NEUTRON CAPTURE THERAPY

Neutron capture therapy [5,6] is an experimental form of highly localized radiation therapy for various forms of cancer. It consists in injecting the patient with a B-10 tagged chemical agent that preferentially concentrates in the tumor. The patient is then irradiated by a neutron beam. This isotope of boron (B-10) is a strong neutron absorber and emits two charged particles:



The two charged particles (alpha and lithium-7) create substantial localized damage to cancer cells. The irradiated area is around 10 microns (stopping distance for alpha particles). This technique has been extensively tested on animals and tried on humans a few times. It has been used on brain tumors as well as tumors around the neck. Clinical trials have been conducted on cancer patients in Japan, in the US and in Finland.

Another more drastic form of neutron therapy uses fast neutrons [7] to blast out cancerous tumors that are not too deeply located. This is appropriate for aggressive forms of prostate or salivary gland tumors. There are three such centers offering fast neutron radiation therapy in the US.

## OTHER BENEFICIAL APPLICATIONS OF RADIATION EFFECTS

Other useful applications of neutron irradiation have been identified. Irradiating electronics components has been found to help enhance their performance. For example,

irradiating diodes increases their electrical resistance under high AC frequencies (100 MHz). Fast neutron irradiation of memory chips in bulk as a quality control step helps eliminate units that are prone to “soft” computer failure. After irradiation, chips are tested in realistic working conditions; only well-performing ones are kept. This helps reduce bit reset chip failures by a factor of 10. Radiation damage in silicon reduces the intrinsic resistivity thereby favoring better dissipation of charge buildup that may be caused by ionizing background radiation. This reduces bit reset problems in computer chips. Fast neutron irradiation has also been found to improve the hardness of drill bits and other hard-working components. Radiation damage creates enough lattice defects and slip planes in the crystal structure to allow better diffusion of localized microstresses. Neutron irradiation has been found to improve the toughness and durability of frying pans coatings. It introduces crosslinks in the plastic coating material.

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## NEUTRON SCATTERING

Most people are familiar with microscopy which can view the morphology of samples in real space. Optical microscopy magnifies micron size structures while electron microscopy can observe down to nanometer size structures. Neutron scattering can also probe structures at the nanometer scale but works in the so-called reciprocal (or Fourier) space. Neutron scattering is getting more popular as a "routine" characterization technique for a wide range of practical applications. A few of these applications are described here.

### THE NIST GUIDE HALL

The NIST Center for Neutron Research guide hall uses cold neutrons for various types of neutron scattering. These include inelastic/quasielastic neutron scattering, neutron diffraction, small-angle neutron scattering and neutron reflectometry. Neutron diffraction, small-angle neutron scattering and neutron reflectometry are elastic scattering methods since there is no energy change during the scattering process.

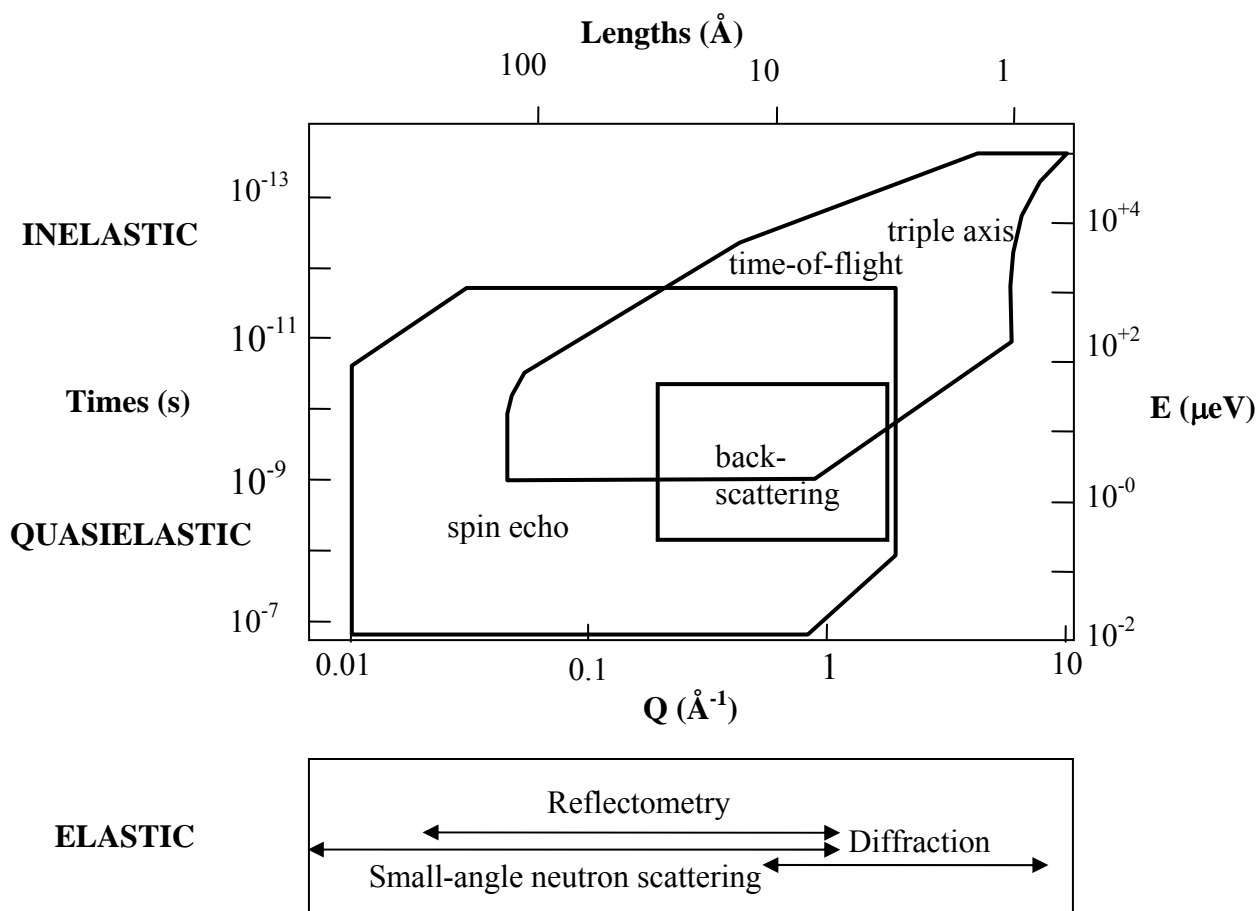


Figure 1: Energy/size scale diagram representing the windows of the various neutron scattering techniques.

All instruments in the guide hall use cold neutrons (with wavelengths higher than 4 Å). Cold neutrons are produced by cooling thermal neutrons down to 20 K temperature in a liquid hydrogen cold source.

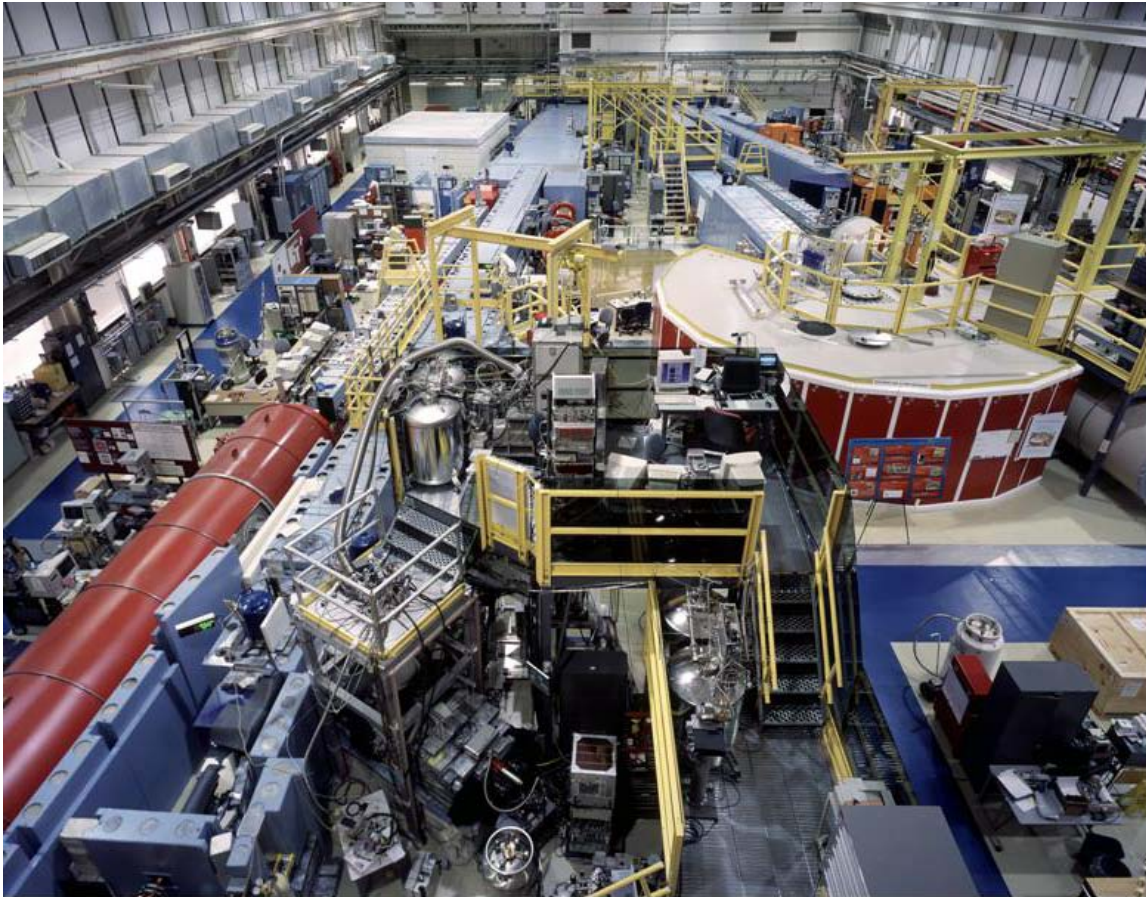


Figure 2: Picture of the NIST Center for Neutron Research guide hall. The red vessel to the left is part of a 30 m small-angle neutron scattering instrument. The red shielding cover on the right is part of the time-of-flight quasielastic neutron scattering instrument.

## THE DEUTERATION METHOD

The main advantage of neutron scattering over x-ray scattering is the possibility of deuterating parts of a sample in order to enhance their contrast. The deuteration method consists in replacing hydrogen atoms by deuterium ones in the sample. This is equivalent to the staining method in electron microscopy.

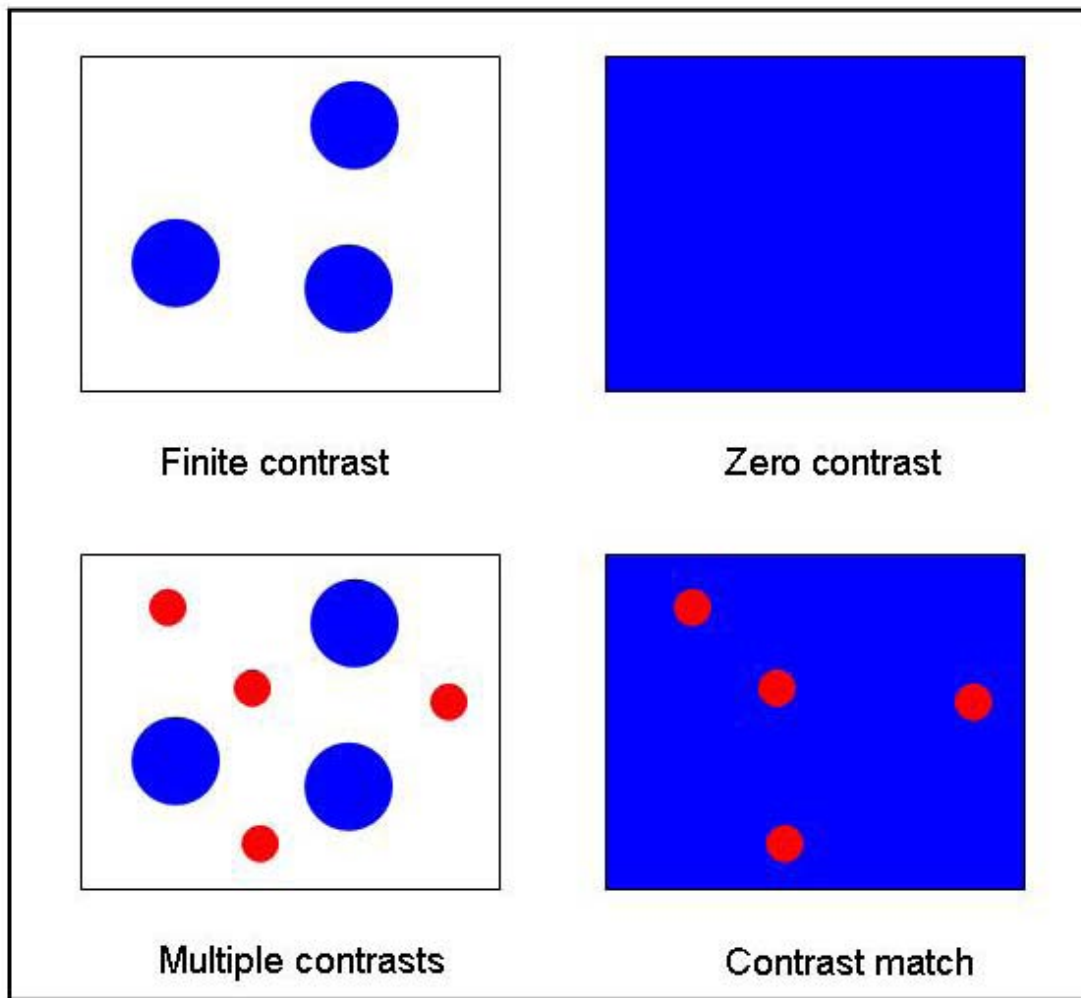


Figure 3: The partial deuteration method helps adjust the contrast of specific components in the sample.

## SMALL-ANGLE NEUTRON SCATTERING

Due to the research interests of this author in small-angle neutron scattering (SANS), applications related to that technique will be emphasized. SANS is a popular scattering method for the characterization of structures from the near atomic to the near micron size scales [1]. This is referred to as the nanometer size scale. A SANS instrument consists in 4 steps: monochromation, collimation, scattering and detection. Monochromation is performed using a so-called velocity selector which selects a specific cold neutron wavelength (around 5 Å) from the incident distribution. Collimation consists in a source aperture and a sample aperture which focus the beam to a small spot on the 2D neutron detector. The area neutron detector uses the  $\text{He-3}(n,p)\text{H-3}$  nuclear reaction to detect the position of scattered neutrons on a 128\*128 grid.

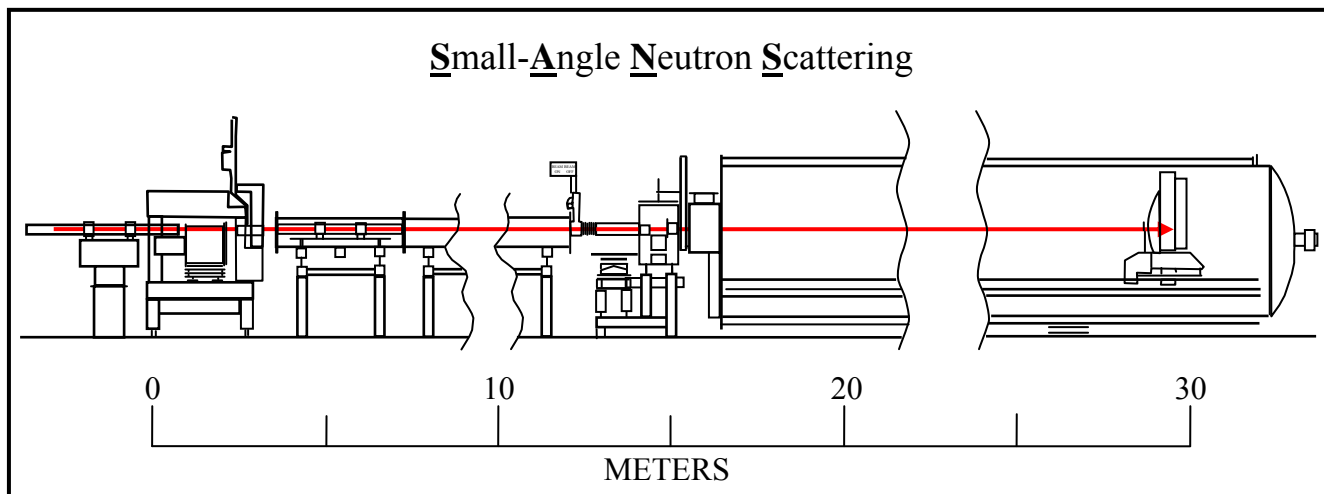
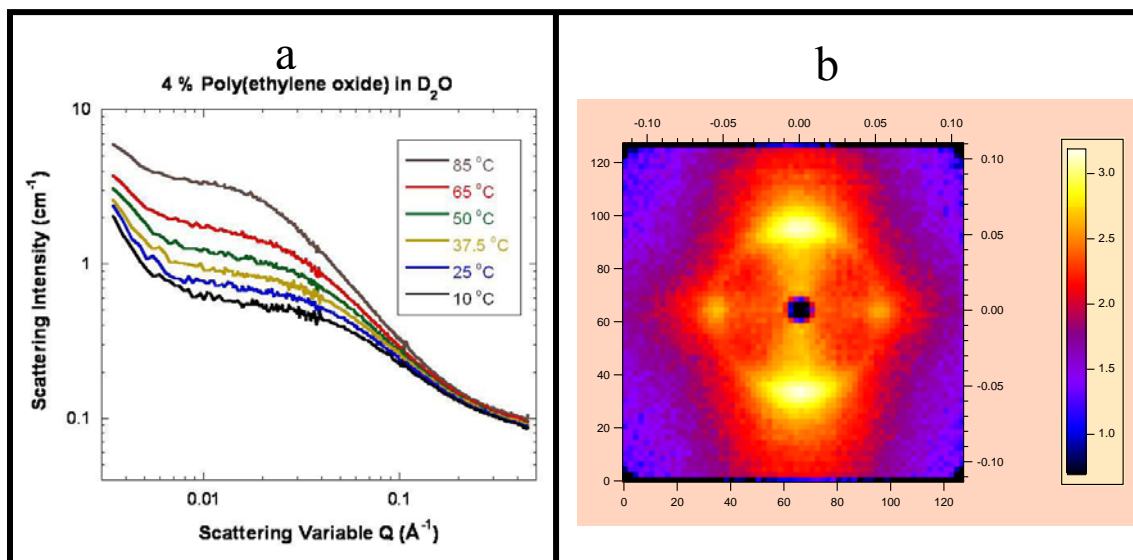


Figure 4: Schematic representation of a 30 m SANS instrument.

SANS has received wide use in the following research areas: polymers, complex fluids, biology, material science and magnetism. SANS measures the density-density correlation function in reciprocal space. Representative SANS spectra are included to show the variety of research topics conducted using this technique. Deuterated water (also called heavy water) is used in order to enhance the neutron contrast.



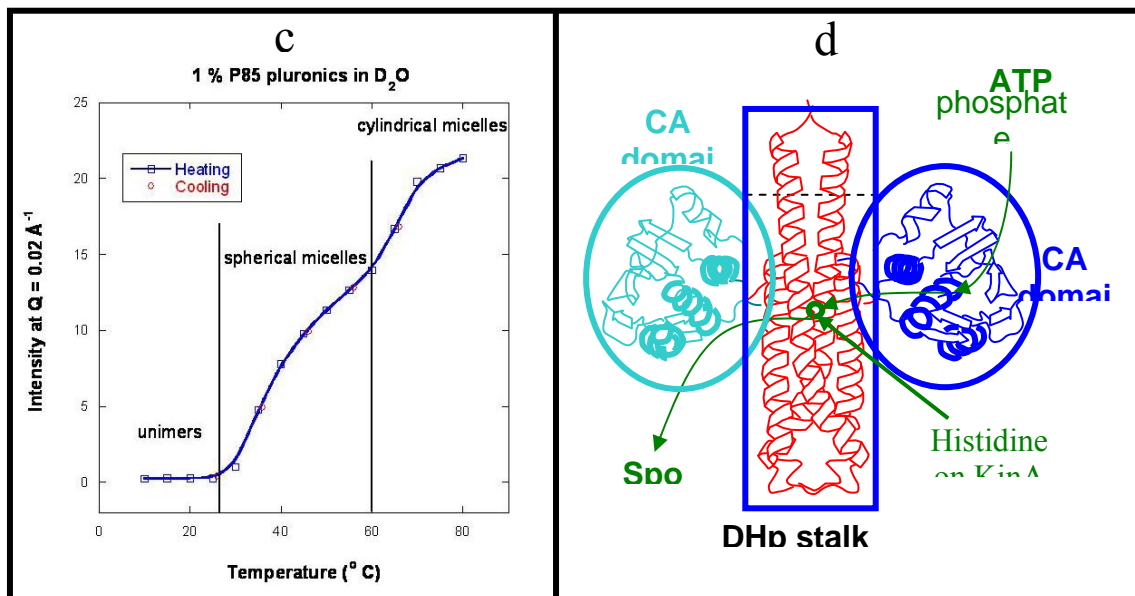


Figure 5: Assortment of representative figures (a) SANS data from a polymer solution, (b) SANS image for a sheared complex fluid (c) low-Q SANS data showing the formation of spherical and cylindrical micelles and (d) schematic representation of a protein complex.

Some practical (i.e., applied research) SANS applications are described next.

## WAX BUILDUP IN DIESEL ENGINES

Diesel engines do not run well in cold climates. Below  $10^{\circ}\text{C}$ , filters clog up causing engine problems and leading to mechanical equipment failure. This is caused by wax crystals buildup inside the fuel system at these low temperatures. Using the SANS technique, the Exxon petroleum company found that adding small amounts of polyolefin copolymers to diesel fuels helps reduce wax crystal buildup thereby solving the problem. The time scale between discovery and full scale testing with the improved fuel additive was less than 3 years [2].

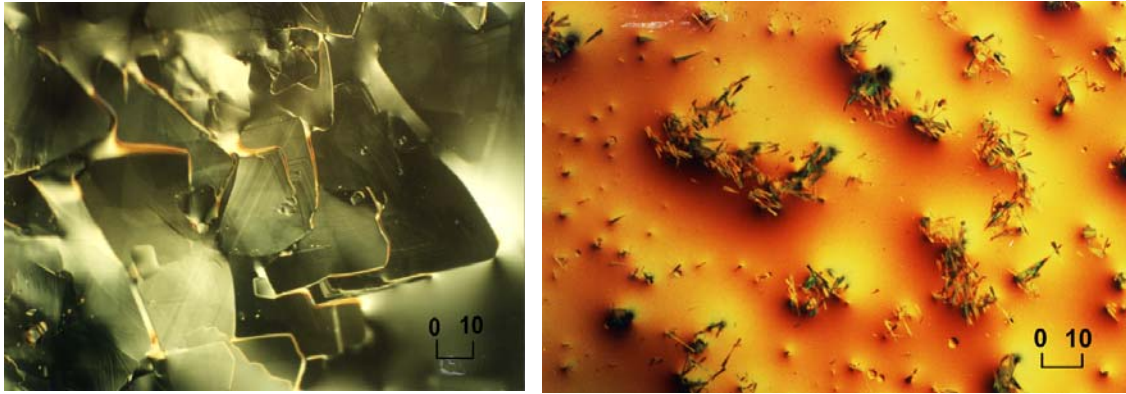


Figure 6: Micrographs of the diesel fuel without (left) and with (right) the copolymer additive. Adding the copolymer reduces wax buildup.

## **MICROSTRUCTURAL CHANGES IN REACTOR VESSELS**

The mechanism of embrittlement of reactor pressure-vessel steels following long term radiation exposure was investigated by SANS. Irradiation was performed using either a proton accelerator or neutron beams. Steel types and exposure conditions such as temperature were varied. The alloy nanostructures were determined and correlated to radiation hardening conditions [3].

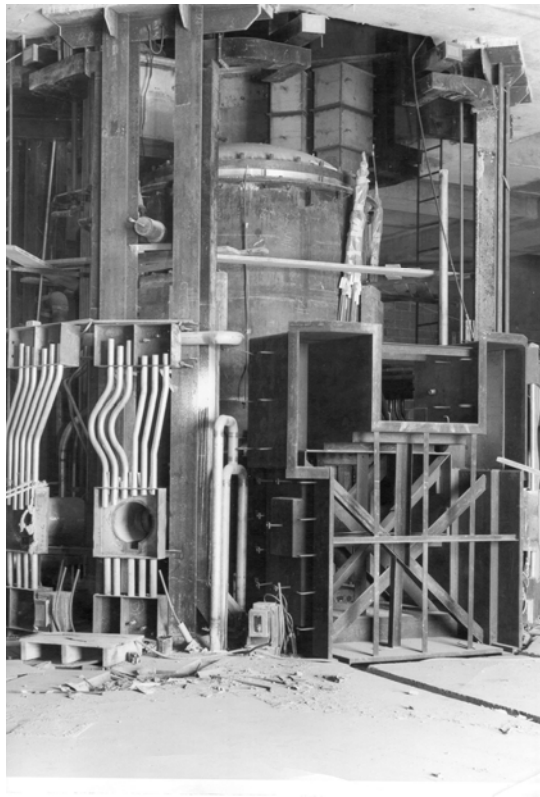


Figure 5: Reactor vessels become brittle due to long term radiation hardening.

## HYDROGEN FUEL CELLS

The hydrogen fuel cell technology has become an active area of research using SANS. Fuel cells use hydrogen to produce electricity. Hydrogen fuel is fed to the anode while ambient oxygen is used on the cathode side. At the anode, a catalyst causes hydrogen to ionize into protons and electrons. Polymer membranes were found to be effective at letting only the protons pass through to the cathode. The electrons circulate along an external circuit thereby creating an electrical current. SANS has been used to characterize porosity in some polymer membranes. It was found that channel pore sizes less than 50 Å enhance proton conductivity. Copolymer morphologies can be adjusted to obtain the desired pore sizes and structures. These SANS investigations were conducted using in-situ humidity and temperature control [4].

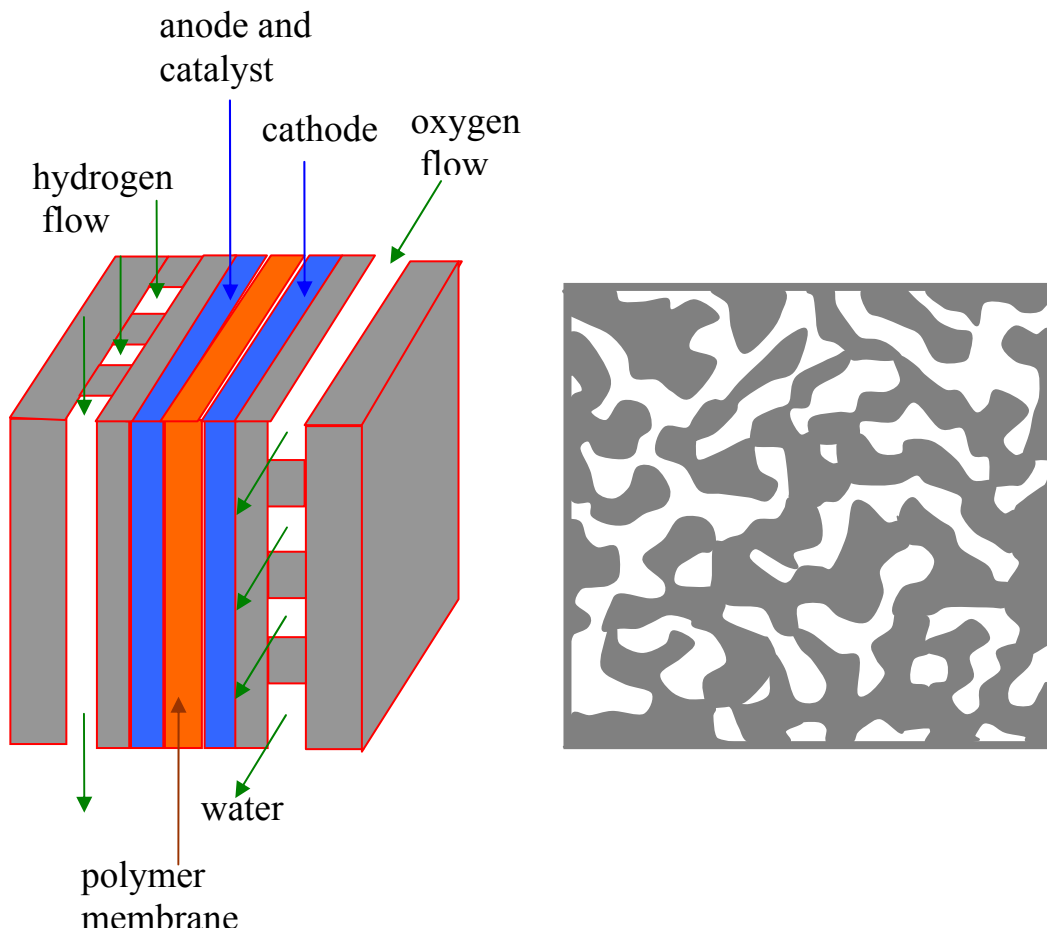


Figure 6: Schematics of a hydrogen fuel cell (left) and of a fuel cell membrane (right).

## CHARACTERIZATION OF VARIOUS MARBLES

Marble is used to make statues and monuments. It is preferred because of its low weathering attribute. Marble rocks deriving from metamorphic evolution are difficult to identify. SANS has been used to investigate a number of Italian white marbles. Parameters characterizing the mesoscale structural arrangement (such as grain size and fractal dimension) obtained from SANS have been correlated with the metamorphic history. These results help identify the source provenance and the authentication of ancient marble artifacts [5]. Michelangelo loved to sculpt with white marble. It is reported that when he finished his masterpiece statue David, he stepped back and uttered “Da\*\* it. Speak to me!”.



Figure 7: Marble statue of David by Michelangelo (left) and texture of a marble sample (right).

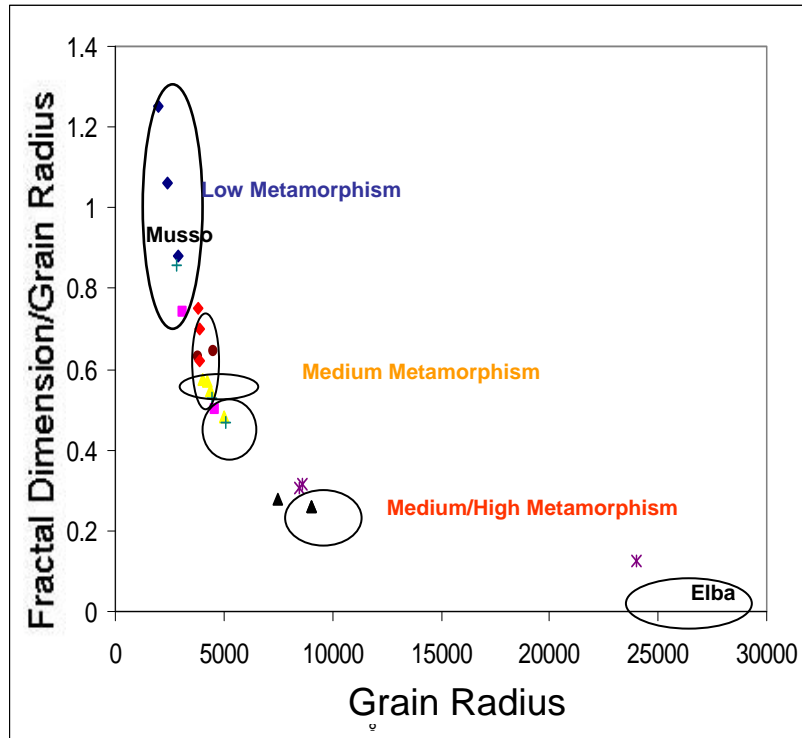


Figure 8: Fractal dimension over grain radius vs grain radius for various Italian marbles obtained from SANS.

## CONSERVATION SCIENCE

A host of chemical synthesis and physical characterization methods have been brought to bear in the field of conservation science and restoration of cultural heritage. Gels containing various surfactants (specific soap products) are used to gently clean old paintings without damaging them. The old method of protecting paintings was to apply a thin coat of polymers. This layer was found to degrade over time thereby worsening the condition of the paintings. The tools of nanoscience such as SANS have been applied successfully to characterize the gels materials used and understand why some are more effective than others. The cleaning gels are applied directly on the canvas and achieve substantial results. Such projects include restored masterpieces of Beato Angelico, Taddeo Gaddi, Pierodella Francesca and Santidi Tito [6]. This technique has also been applied to Mayan wall paintings (Mexico) and to the deacidification of paper [7] and wood from the Vasa warship (Stockholm) [8]. The special gels used in these applications are referred to as nanosponges [9].

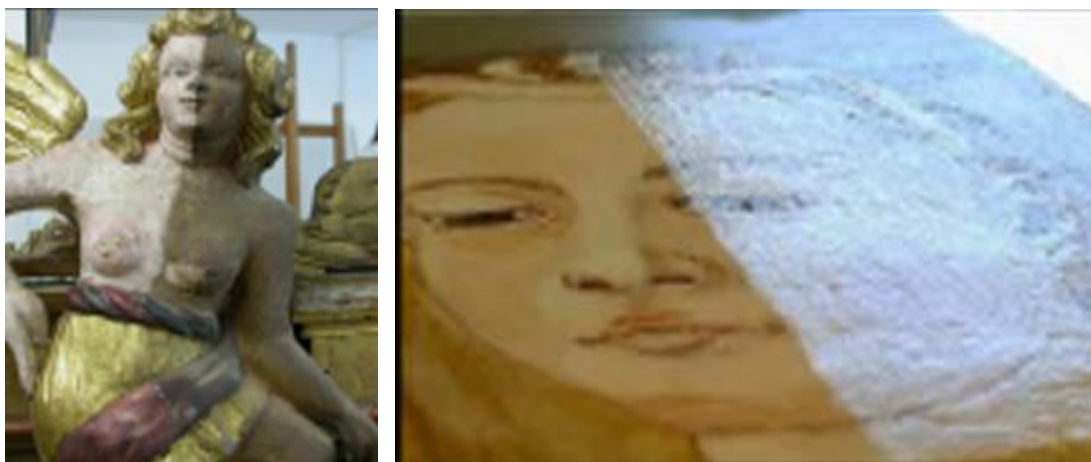


Figure 9: Special gels are applied to paintings to clean and restore them to a healthier condition. The clear (left) portions have been cleaned and the dark (right) portions have not.



Figure 10: Small wood pieces of an old ship were investigated to assess the deacidification method using special gels.

## **EFFECT OF IBUPROFEN ON BIOCOMPATIBLE PLURONICS**

Ibuprofen is a non-steroidal anti-inflammatory drug; it is used for the relief of symptoms associated with arthritis and of fever and headaches. Ibuprofen tablets are available over the counter and act over a few hours span. A known COX enzyme stimulates blood platelet aggregation thereby mediating pain and fever. Ibuprofen inhibits this blood clot formation process thereby relieving pain [10]. SANS measurements on biocompatible Pluronics have shown that ibuprofen acts as a co-surfactant; it helps balance the hydrophobic/hydrophilic competing effects thereby enhancing the antiplatelet effect [11].

## **ARTIFICIAL CORNEA REPLACEMENT MATERIAL**

Mild vision impairment results from the loss of elasticity of the cornea. Efforts have been made to find cornea replacement. Hydrogels are a natural route to find suitable materials. Single hydrogel networks are typically too weak since the water content is too high. Interpenetrating network (IPN) hydrogels seem to possess the right mechanical strength, water solvation and desired permeability for cell nutrients (such as glucose). A research group involving the Stanford Medical School has characterized such high strength IPN hydrogels. SANS measurements have been performed to unravel the structure of poly(ethylene glycol)/poly(acrylic acid) high strength interpenetrating network hydrogels as candidates for cornea replacement material [12,13].

## **OBSIDIAN HYDRATION RATES**

Geological and archeological obsidian samples were used to reconstruct evolution of the climate during the Paleolithic era. The Paleolithic era covers between 2.5 million and 12,000 years ago and spans from the Stone Age to the pre-agricultural stage of human evolution. Obsidian is a volcanic glass used by early humans to make tools. Their hydration rates have been used as a chronometer to analyze water content in the atmosphere and therefore assess climate changes in the distant past. Isotopically labelled water samples were used to further hydrate obsidian glass samples. The labelled water samples contained deuterium (replacing hydrogen) and oxygen-18 (replacing oxygen-16). The hydration profiles were determined using secondary ion mass spectroscopy and neutron reflectometry [14]. This method yielded a better understanding of the diffusion of atmospheric moisture into obsidian and its effect on water trapped at the time of formation of this volcanic glass.

## **ENGINEERING MATERIALS**

In order to understand the mechanical properties of materials, it is important to map out their microstresses. These are the localized stresses that develop within the atomic

structure. Neutron diffraction is used to measure such microstresses by monitoring well-defined d-spacings (i.e., atomic spacings) characterizing the atomic structure. Using a highly collimated incident neutron beam and measuring the beam diffracted from a well defined sample volume is a technique referred to as residual stress measurement [15]. This technique has been applied to map out residual stresses in many engineering materials including blades used in turbo engines, hard working machining tools, tips of sharp objects, etc.

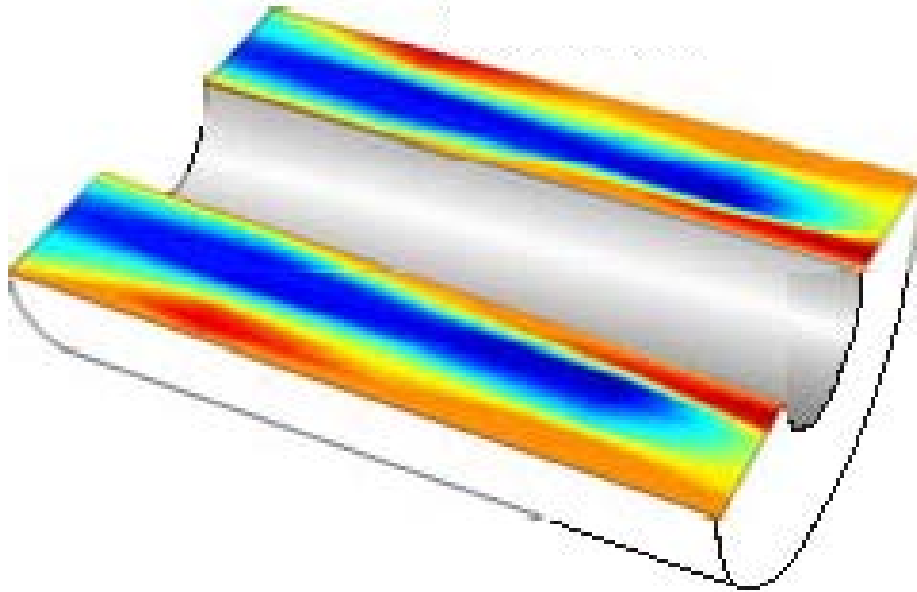


Figure 11: Color map of the residual stresses in a pressure vessel.

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## **PERSPECTIVE**

Nuclear applications consist in the production of weapons materials, in the generation of electricity, and in a host of other practical applications. The focus here was on the third item.

Since their first demonstration in 1945, nuclear weapons have been developed on a massive scale by technologically advanced nations. The cold war between the former Soviet Union and the United States has seen an escalation in the production of nuclear weapons. Each side stockpiled thousands of intercontinental ballistic missiles carrying nuclear warheads. These were used as strategic deterrents against nuclear attacks. The idea was to be able to obliterate the other side many times over in retaliation. The US star wars program of the 1980s set out to deploy an assortment of defensive and offensive weapons in orbit that would be ready to be used at a moment's notice. The end of the cold war released the escalation mentality and lowered the effort to produce nuclear weapons. The focus shifted to deterring potential rogue states from producing nuclear weapons. Most of the nuclear nations acquired their capabilities before the 1980s. These are the US, Russia, France, the United Kingdom, Israel, China, India and Pakistan. North Korea joined the group later.

Electrical power production is the second major use of nuclear energy. Many technologically advanced nations have invested heavily in this form of energy production, especially those with little or no oil reserves. For instance, France covers some 80 % of its energy needs from nuclear. This is to be compared to 20 % in the US. There are over 400 nuclear power generating plants in the world. There are 104 such commercial stations in the US most of which were constructed over 30 years ago. Construction hastened in the aftermath of the oil crisis of the 1970s. The output power of power producing stations got scaled up to around 1,000 MW (electric) rather quickly. This opened up a host of safety issues with their operation. Two nuclear accidents (at Three Miles Island in 1979 and at Chernobyl in 1986) as well as a "green" wave against nuclear technology put a stop to that trend. Not many licenses have been issued for the construction of new nuclear power plants in the US for the past 30 years. Some power plants were cancelled at an advanced stage of construction (over 70 % complete). The word "nuclear" acquired such a negative connotation that green movements opposed their construction which incurred huge cost overruns. Decreasing enrolment in nuclear engineering departments forced some of them to close and others to redirect their focus. Dwindling oil reserves in the world and recent skyrocketing prices for crude oil are bringing the nuclear wave back. The US is contemplating the construction of new nuclear power generating stations again. Proponents argue the "green" nature, free of carbon dioxide emission. Opponents point to the nuclear waste problem that has yet to be resolved.

The third leg of the nuclear technology stool covers the panoply of "other" (so-called practical) applications described in the document. These are based at nuclear research

reactors. There are presently some 22 research reactors in the US, 13 of which have a power of 1 MW or less. The major facilities are located at federal government laboratories and were initially constructed in the 1960s. Many nuclear research reactors were built at universities as well in the 1960s. Some have received upgrades but many had to be shutdown due to tight budget constraints. Only a couple of research reactors have been constructed over the past 30 years. University-based nuclear reactors are a dying breed! Some manage to survive by undertaking business ventures using their irradiation facilities. Some generate much needed funds by irradiating Topaz, through the transmutation doping of silicon and by producing radioisotopes. Such irradiation endeavors require complex hot-chemistry expertise. A law mandating that all nuclear research reactors move to a medium-to-low enrichment fuel cycles was passed in the US in late 1970s. The specter of that law remains looming even though it has not been enforced. Many facilities are still using high enrichment. Neutron scattering has been the driving force behind most of the upgrades and expansion efforts of nuclear research reactors. It has managed to grow steadily raising the oversubscription rates of neutron scattering facilities. Neutron scattering has moved to a routine characterization status attracting interest in widely diversified research areas.

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